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Plate Margin Deformation and Active Tectonics along the northern edge of the Yakutat Terrane in the Saint Elias Orogen, Alaska and Yukon, Canada --Manuscript Draft--

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Abstract:	The northwest directed motion of the Pacific plate is accompanied by migration and collision of the Yakutat terrane into the cusp of southern Alaska. The nature and magnitude of accretion and translation on upper crustal faults and folds is poorly constrained, however, due to pervasive glaciation. In this study we used high-resolution topography, geodetic imaging, seismic, and geologic data to advance understanding of the transition from strike-slip motion on the Fairweather fault to plate margin deformation on the Bagley fault, which cuts through the upper plate of the collisional suture above the subduction megathrust. The Fairweather fault terminates by oblique-extensional splay faulting within a structural syntaxis, allowing rapid tectonic upwelling of rocks driven by thrust faulting and crustal contraction. Plate motion is partly transferred from the Fairweather to the Bagley fault, which extends 125 km farther west as a dextral shear zone that is partly reactivated by reverse faulting. The Bagley fault dips steeply through the upper plate to intersect the subduction megathrust at depth, forming a narrow fault-bounded crustal sliver in the obliquely convergent plate margin. Since ≈ 20 Ma the Bagley fault has accommodated more than 50 km of dextral shearing and several kilometers of reverse motion along its southern flank during terrane accretion. The fault is considered capable of generating earthquakes because it is linked to faults that generated large historic earthquakes, suitably oriented for reactivation in the contemporary stress field, and locally marked by seismicity. The fault may generate earthquakes of $M_w \leq 7.5$.
Suggested Reviewers:	Peter Haeussler, PhD

	Research Geologist, USGS pheuslr@usgs.gov Peter Haeussler is very familiar with Alaskan tectonics. Drawback is that he has worked and published with R.L. Bruhn several years ago. So you may consider that a conflict of interest. But frankly, Peter will give an honest review and he is very knowledgeable concerning problems of Saint Elias tectonics. Phillip Armstrong, PhD Professor, California State Univ. - Fullerton parmstrong@Exchange.FULLERTON.EDU Phil Armstrong is a thermochronologist and structural geologist who is working in southern Alaska. He has not worked specifically in the Saint Elias region, but he has now completed considerable work in adjacent areas. Thus he is an expert in terms of thermochronology but also he is not directly involved in the Saint Elias area nor the STEEP project. Jeff Freymueller, PhD Professor, University of Alaska (Fairbanks) jeff.freymueller@gi.alaska.edu Dr. Freymueller and his PhD student Julie Elliott (now Dr. Elliott) completed the most recent geodetic survey (GPS) of plate margin deformation in the Saint Elias region, including the area covered in the Bruhn et al. submitted manuscript. Charles H. Estabrook, PhD National Science Foundation cestabro@nsf.gov Dr. Estabrook carried out a seminal study with his colleagues on the 1979 St. Elias earthquake. We used the results of his study to construct a fault model for the eastern Saint Elias region. Also, Dr. Estabrook is familiar with southern Alaska plate margin tectonics and earthquakes. However, he is currently with the EarthScope program at NSF, and we are not sure if that would create the perception of a conflict of interest. He would be an excellent reviewer if he is able to do so.
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Plate Margin Deformation and Active Tectonics along the northern edge of the Yakutat Terrane in the Saint Elias Orogen, Alaska and Yukon, Canada

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ABSTRACT

The northwest directed motion of the Pacific plate is accompanied by migration and collision of the Yakutat terrane into the cusp of southern Alaska. The nature and magnitude of accretion and translation on upper crustal faults and folds is poorly constrained, however, due to pervasive glaciation. In this study we used high-resolution topography, geodetic imaging, seismic, and geologic data to advance understanding of the transition from strike-slip motion on the Fairweather fault to plate margin deformation on the Bagley fault, which cuts through the upper plate of the collisional suture above the subduction megathrust. The Fairweather fault terminates by oblique-extensional splay faulting within a structural syntaxis, allowing rapid tectonic upwelling of rocks driven by thrust faulting and crustal contraction. Plate motion is partly transferred from the Fairweather to the Bagley fault, which extends 125 km farther west as a dextral shear zone that is partly reactivated by reverse faulting. The Bagley fault dips steeply through the upper plate to intersect the subduction megathrust at depth, forming a narrow fault-bounded crustal sliver in the obliquely convergent plate margin. Since ≈ 20 Ma the Bagley fault has accommodated more than 50 km of dextral shearing and several kilometers of reverse motion along its southern flank during terrane accretion. The fault is considered capable of generating

earthquakes because it is linked to faults that generated large historic earthquakes, suitably oriented for reactivation in the contemporary stress field, and locally marked by seismicity. The fault may generate earthquakes of $M_w \leq 7.5$.

INTRODUCTION

The Saint Elias and eastern Chugach Mountains of Alaska and the Yukon, Canada provide a classical locality to study relationships between glaciation, tectonics and landscape evolution (Figure 1; Worthington et al., 2010; Enkelmann et al., 2010; Berger and Spotilla, 2008; Meigs et al., 2008; Jaeger et al., 2001; Meigs and Sauber, 2000). Glaciers mask the structural geology where they flow over folds and faults that form the tectonic framework of the Saint Elias orogen (Bruhn et al., 2004; 2010), erode and transfer large volumes of rock detritus between the mountains and offshore realm (Hallet et al., 1996; Jaeger et al., 2001), and modulate the tectonic stress field by creating transient loads on the lithosphere (Sauber et al., 2000; Sauber and Molina, 2004; Doser et al., 2007; Sauber and Ruppert, 2008). Regional faults that are mostly buried by glaciers include the Fairweather fault, the Malaspina and Bering Glacier faults, and the Bagley fault that cuts through the spine of the main range of the Saint Elias Mountains (Figure 2). Although one of the most spectacular geomorphic features of the orogen, the Bagley fault remains cryptic in terms of its tectonic history and the nature and magnitude of current motion. Here, we use new geodetic imaging, topographic, seismic and geologic data to inform interpretations concerning the structure, kinematics and seismic potential of the Bagley Fault. In addition, we use new glacier morphology and flow dynamics data to infer the topography and structure of the bedrock that lies below the ice.

TECTONIC SETTING OF THE YAKUTAT BLOCK

The Yakutat microplate is colliding along the southern Alaskan plate margin at a rate of ≈ 43 -50 mm/yr (Figure 1; Plafker, 1987; Plafker et al., 1994; Sauber et al., 1997; Elliott et al., 2010). The microplate is a fragment of oceanic plateau with thick basaltic crust overlain partly by Cretaceous flysch and *mélange*, and blanketed by Tertiary strata (Christeson, 2010; Worthington et al., 2012). The tectonically off-scraped and deformed rocks of the microplate form the ‘Yakutat terrane’ within the Saint Elias orogen, while the basaltic crust and mantle of the microplate is subducted beneath the plate margin.

The rise of the Saint Elias orogen overlapped in time with the onset of glaciation, resulting in deposition of the coarse grained glacial till and glacial marine deposits of the late Miocene to Quaternary Yakataga Formation (Eyles et al., 1991), much of which is uplifted and deformed by faulting and folding (Plafker, 1987). Offshore in the Gulf of Alaska, the Yakutat microplate abuts the Pacific Plate along the Transition Fault, a prominent submarine escarpment created by transform motion between the tectonic plates. Subduction of the Yakutat lithosphere beneath southern Alaska occurs along a gently dipping megathrust with profound and far-reaching effects on the tectonics and landscape of interior Alaska (Ferris et al., 2003; Eberhart-Phillips et al., 2006; Bruhn and Haeussler, 2006; Haeussler, 2008; Abers, 2008).

The arcuate geometry of the Alaskan plate margin together with the NNW-directed relative motion of the Yakutat microplate causes a marked change in the obliquity of convergence within the Saint Elias orogen. Deformation in the eastern part is dominated by dextral strike-slip faulting along the Fairweather fault with only a narrow coastal thrust belt within the edge of the Yakutat microplate (Plafker, 1987; Doser and Lomas, 2000; Bruhn et al., 2004). Peaks of the

80 Fairweather Range tower above the eastern side of the Fairweather fault reflecting slow and
81 diffuse deformation that extends far into the continental interior to the east and north of the
82 transform fault boundary (Mazzotti et al., 2003; Elliott et al., 2010). The plate boundary bends
83 abruptly westward at the northern end of the Fairweather fault creating a structural syntaxis that
84 is a locus of rapid tectonic uplift and exhumation (Plafker, 1987; Bruhn et al., 2004; Spotila and
85 Berger, 2008; Enkelmann et al., 2008, 2009; Koons et al., 2010; Chapman et al., 2012). West of
86 this syntaxis the Chugach – Saint Elias fault is the north dipping suture between tectonically
87 accreted rocks of the Yakutat terrane and the overlying metamorphic and igneous rocks of the
88 Early Tertiary plate margin of southern Alaska (Figure 2; Plafker, 1987). The Bagley fault cuts
89 through the Alaskan plate margin north of the suture creating a narrow sliver of crust that is
90 bounded to the south by the Chugach – Saint Elias fault and to the north by the Bagley fault.
91 Tectonic accretion of the Yakutat terrane together with southward and eastward propagation of
92 the subduction de'collement created the wide foreland fold and thrust belt within this central
93 segment of the orogen (Plafker, 1987; Bruhn et al., 2004; Chapman et al., 2008; Wallace, 2008;
94 Pavlis et al., under review).

95
96 The Alaskan plate margin curves towards the Aleutian trench in the westernmost part of the Saint
97 Elias orogen (Figure 1,2) resulting in complex re-folding and faulting that affects both the
98 tectonic sliver of the upper plate and the previously deformed rocks of the Yakutat terrane (Bruhn
99 et al., 2004). The accreted terrain is partly indented into the plate margin, but it is also escaping
100 towards the southwest over the northeastern part of the Aleutian megathrust (Bruhn et al., 2004;
101 Pavlis et al., 2004; Elliott, 2011). Geological evidence for active deformation includes sinistral
102 faulting on oblique-slip faults (Pavlis and Bruhn, 2011; McCalpin et al., 2011), thrust faulting

(Bruhn et al., 2010; Chapman et al., 2011), and structural reactivation of a deformed remnant of the Chugach – Saint Elias suture (Figure 2; Bruhn et al., 2006; McCalpin and Carver, 2009). Anti-slope fault scarps and landslides in mountain blocks attest to the instability of the steep and recently de-glaciated slopes (e.g. – Li et al., 2010; McCalpin et al., 2011).

ROLE OF THE BAGLEY FAULT – HISTORY AND PREVIOUS WORK

The Bagley fault is buried beneath the ice filled troughs and basins of the Seward Glacier, the Bagley Icy Valley and Martin River Glacier (Figure 2, 3). The fault is bounded below by the subduction megathrust, links to the Fairweather fault beneath the upper Seward Glacier in the east, and intersects the WSW trending fault system at the Martin River Glacier to the west. The Bagley fault may continue farther westward beneath the Miles Glacier as far as the Copper River. Campbell et al. (1986) suggests that the fault dips steeply to depths of 5 – 6 km based on modeling of the regional gravity field. This structural configuration creates a narrow fault-bounded sliver in the Alaskan plate margin that may partition displacements between thrust and strike-slip motion (Bruhn et al., 2004).

Rugged mountains and linear glacier-filled valleys dominate the landscape surrounding the Bagley fault (Figure 2,3). Five thousand meter peaks including Mount Logan (5959 m) and Mount Saint Elias (5489 m) tower above the Seward Glacier basin and the eastern end of the Bagley Ice Valley. The Barkley and Waxell Ridges form steep north-facing mountain walls along the southern side of the ice valley, and Mount Tom White (3013 m) dominates the skyline of the eastern Chugach Mountains where the Bagley fault enters a contractional fault bend (Figure 2). A topographic saddle at the confluence of the eastern and western arms of the Bagley Ice Valley

marks the intersection of the Bagley fault with one or more faults that lie beneath the Bering and Tana Glaciers (Bruhn et al., 2004, 2010; Spotila and Berger, 2008). Seismicity is sparsely distributed along the length of the fault with events clustering beneath the western Bagley Ice Valley (Doser et al., 2007) and surrounding the Quintino Sella and Jefferies Glaciers. Seismicity is scattered beneath the Seward Glacier at the eastern end of the Bagley fault, but is clustered south of the basin beneath the Malaspina Glacier and foreland fold and thrust belt (Figure 4; Ruppert, 2008; Sauber and Ruppert, 2008; Doser et al., 1997).

Information concerning the structural geology of the Bagley fault is sparse and mostly circumstantial. The fault is buried beneath glaciers, the surrounding bedrock is older than the collision of the Yakutat microplate, and there are few Quaternary deposits to study for evidence of recent rupturing (Campbell and Dodge, 1978; Bruhn et al., 2004; Richter et al., 2005). The Bagley fault was considered part of the Contact fault plate boundary because it juxtaposes rocks of different tectonic terranes that accreted before arrival of the Yakutat terrane. The cessation of movement was cited at ≈ 50 Ma based upon the age of a little deformed granitic pluton within the fault zone near the head of the Miles Glacier (Figure 2; Plafker and Lanphere, 1974; Plafker, 1987). However, recently acquired thermochronology data reveal that the pluton was uplifted and exhumed by several kilometers within the last 5 Ma to 10 Ma, during collision and accretion of the Yakutat terrane (Fig. 3; Berger et al., 2008b). Farther east along the Bagley fault the mountains along the southern side of the ice valley were also uplifted and exhumed during the last several million years, presumably by reverse faulting within the plate margin (Chapman et al., 20008; Berger and Spotilla, 2008; Spotila and Berger, 2008; Enkelmann et al., 2010).

Geodetic data in the region of Figure 2 include trilateration (Savage and Lisowski, 1986; 1988), VLBI (Very Long Base Line Interferometry) and GPS campaign-style measurements (Sauber and Molnia, 2004) obtained between 1979 and 2000, and a regional network of GPS campaign-style measurements completed during the Saint Elias Erosion and Tectonics project in the period 2005 – 2009 (Elliott, 2011). The results of the most recent study differ from earlier ones that postulated dextral shearing along or surrounding the Bagley fault in the Bagley Ice Valley (Savage and Lisowski, 1986; Sauber and Molnia, 2004). Elliott's (2011) tectonic block model of the orogen requires no contemporary motion along the Bagley fault within the limits of resolution of several mm/yr, but she does place the northeastern boundary of a small Bering Glacier tectonic block near the intersection between the Bering Glacier and Bagley faults. The Bering Glacier block is moving southwest relative to other parts of the orogen and relative to the newly defined Elias tectonic block that is located to the north and west of the Saint Elias Mountains. Although the conclusions of the various geodetic studies differ with respect to strike-slip motion on the Bagley fault, all identify active deformation near the intersection of the Bering Glacier and Bagley faults.

RESEARCH DATA AND PROCEDURES

Our research goal is to infer the role of the Bagley fault in accommodating deformation during collision and accretion of the Yakutat terrane. Given that glaciers blanket much of the landscape we rely primarily upon remote sensing techniques that augment available data from published structural (e.g – Plafker, 1987; Bruhn et al., 2004; Chapman et al., 2008) and thermochronology studies (O'Sullivan et al., 1996; Berger and Spotilla, 2008; Berger et al., 2008a, 2008b; Enkelmann et al., 2009; 2010; Spotila and Berger, 2008; Meigs et al., 2008).

172

173 Elevation data for analysis of the topography was obtained from the Ice, Sea and Land Satellite
174 (ICESat; Schutz, 2001; Schutz et al., 2005), Airborne Terrain Mapper (ATM; Krabill et al.,
175 2002), Shuttle Radar Topographic Mission (SRTM; Farr and Kobrick, 2000; Rodriguez et al.,
176 2005; Muskett et al., 2003; 2008, 2009), and the Advanced Spaceborne Thermal Emission and
177 Reflectance (ASTER) Global Digital Elevation Model (GDEM; ASTER GDEM Validation
178 Team, 2009). Elevation posting is 30 m for the ASTER GDEM and SRTM data. A 10 m posted
179 digital elevation model over the eastern Bagley Ice Valley and western part of the upper Seward
180 Glacier by Intermap Technologies was the highest resolution DEM (R. Muskett, personal
181 communication, 2009), and it is used to investigate the surface topography of the eastern Bagley
182 Ice Valley.

183

184 Ice surface velocity was measured with offset tracking methods using both optical and synthetic
185 aperture radar (SAR) data. Optical feature tracking was performed using normalized image cross
186 correlation (COSI-CORR software (Leprince et al., 2007)) on pairs of Landsat images acquired
187 over intervals of 1 month to several years (Cotton, 2011). SAR offset tracking was performed
188 using normalized cross correlation (GAMMA Software, (Strozzi et al., 2002)) on RADARSAT-1
189 Fine Beam, ALOS PALSAR Fine Beam, and ERS1/2 data over intervals of 24 - 45 days (Burgess
190 et al., 2012).

191

192 Optical imagery from the KH-9 satellite, Landsat 7 and 5, and ASTER data were used to map
193 rock type and structure in selected areas, as well as to map spatial patterns of crevasses and folds
194 on glaciers. Ice and rock structures were visualized by draping optical imagery over digital

elevation models. Orientations of tectonic faults and folds that project beneath glaciers were determined by 3-point and linear least-squared calculations to determine strike and dip where field measurements were not available.

GLACIOLOGY AND STRUCTURE OF BAGLEY FAULT

The Eastern Syntaxis – Fairweather and Bagley Fault Interaction

The topography and structure of the orogen rises abruptly where the plate boundary bends from a regional strike of $\approx 319^\circ$ along the Fairweather Fault to roughly east - west parallel to the Chugach – Saint Elias and Bagley faults (Figure 2). This bend or ‘syntaxis’ increases the ratio of convergence to strike-slip motion along the plate boundary from $\approx 0.1:1$ along the Fairweather fault to increasingly compressional strain normal to the Chugach – Saint Elias and Bagley faults (e.g. – see also Figure 7 of Sauber et al., 1993). The resulting increase in transpressional strain drives uplift of the mountains creating some of the highest peaks in North America. Understanding the structural geology of the syntaxis is crucial to our goal of evaluating the role of the Bagley fault in regional tectonics. The eastern end of the fault must interact with the Fairweather strike-slip fault that extends into the spine of the Saint Elias Mountains, and also with the underlying thrust faults that drive uplift of the range.

The syntaxis begins at a 10° counter-clockwise bend in structural and topographic grain at Disenchantment Fjord and culminates at the terminus of the Fairweather fault, where the mountains rotate an additional 30° towards the west into alignment with the Bagley and Chugach – Saint Elias faults (Figure 5). The low-lying foreland beneath the Malaspina Glacier is thrust obliquely beneath the mountains along the Bancas - Esker Creek and Malaspina faults in this

region (Bruhn et al., 2004; Plafker and Thatcher, 2008) and the Fairweather fault terminates by splaying beneath the upper Seward Glacier (Figure 5; Ford et al., 2003). These faults all ruptured during large to great magnitude earthquakes in the last 110 years. The thrust faults formed parts of the seismic source zones of two M_w 8.1 earthquakes in 1899 (Plafker and Thatcher, 2008). Rupturing along the length of the Fairweather fault in 1958 terminated to the north beneath the upper Seward Glacier, creating an M_w 7.9 earthquake (Tocher, 1960; McCann et al., 1980; Doser, 2010; D. Doser, personal communications, 2011). The M_w 7.4 Saint Elias earthquake in 1979 initiated beneath the mountains north of the Bagley fault and ruptured up to the south and laterally towards the east before arresting along the northern side of the Bagley fault and near the terminus of the Fairweather fault (Estabrook et al., 1992).

Uplifted shorelines surrounding Disenchantment and Russell Fjords as well as an abrupt right-handed jog of the mountain front where the Fairweather fault emerges on shore along the northern side of the Hubbard Glacier, provide geological evidence for the role of faulting within the syntaxis (Figure 6). Rupturing on the Yakutat, Bancas – Esker Creek and Fairweather Boundary fault systems uplifted the shore line as much as 14 m relative to sea level in 1899 (Tarr and Martin, 1912), during thrust faulting and contraction of the crust at high-angle to the Fairweather fault (Plafker and Thatcher, 2008). The 4 km to 4.5 km dextral jog of the mountain front on the northern side of the Hubbard Glacier reflects cumulative displacement on the Fairweather fault during ≈ 100 ka given slip rate estimates between 43 mm/yr and 50 mm/yr (Figure 6; Elliott et al., 2010; Plafker et al., 1978). This amount of displacement is ≈ 1 km less than the lateral offset and deflection of a stream channel by the fault just south of the Hubbard Glacier, suggesting that some of Fairweather fault displacement is transferred onto the

Fairweather Boundary and Bancas – Esker Creek faults within the syntaxis.

The Fairweather fault is marked by several significant structural and geomorphic features where it enters the syntaxis and cuts through the mountains into the basin of the upper Seward Glacier. These include: (1) A 2.5 km long south-facing cliff where the Fairweather fault emerges from beneath the Hubbard Glacier and extends into the trough of the Valerie Glacier (Figure 6). The height of the cliff increases northward from a south-facing monocline on the surface of the Hubbard glacier to a steep south-facing icefall on the lowermost Valerie Glacier that is up to 200 m high (Figure 6). (2) The northeast-dipping thrust fault that crosses the mouth of the Hubbard Glacier presumably represents crustal contraction created by transpression east of the Fairweather fault. This thrust may emanate off the southern side of the Art Lewis Glacier fault forming a one-sided flower structure. There is no geological evidence to demonstrate that the fault is active, but it does form a prominent monoclinal flexure on the surface of the ice where it crosses beneath the Hubbard Glacier, and there is band of enhanced seismicity beneath the mountains that form its hanging wall (Fig. 4). (3) The Valerie Glacier trough necks down in width between an elevation of 970 m and 1830 m where the Fairweather fault rotates several degrees counter-clockwise between two restraining bends (Figs. 5, 6-1Supplement). Narrowing of the trough is caused by enhanced contraction because of the greater misalignment of the fault with respect to plate motion. The dome of bedrock that protrudes into the fault zone at 1830 m is then a transpressional ‘pop-up’ structure. (4) The Fairweather fault extends through the mountain pass at the head of the Valerie Glacier and into a west-plunging glacial trough before terminating beneath the upper Seward Glacier. The fault termination is marked by a northwest-trending splay fault that extends towards the southern flank of Mt. Logan (Ford et al., 2003), and by the

Cascade Glacier thrust fault that lies beneath the outlet valley of the lower Seward Glacier (Figure 5).

The Fairweather and Bagley Faults beneath the Upper Seward Glacier

Geological information concerning the structural geology this region relies on mapping of outcrops in the surrounding mountains and the nunataks that lie within the basin of the upper Seward Glacier (Campbell and Dodds, 1978; Richter et al., 2005). Here, we supplement geological observations by estimating the surface velocity field of ice flow within the basin, and using the velocity field, and the topography and structural fabric of the glacier surfaces to infer the structures at depth.

The directions of the glacier velocity field determined by optical feature tracking of Landsat V scenes acquired one year apart (Figure 7) are similar to those reported by Ford et al. (2003) who used 24 hour repeat-pass SAR scenes and interferometry techniques (InSAR). The velocity magnitudes obtained by optical feature tracking are significantly larger, however, than those reported by Ford et al. (2003); we hypothesize that the higher rate is due to a glacier surge during the period of Landsat scene acquisition in 1986 – 1987 (Muskett et al., 2008). The surging state of the Seward Glacier causes large changes in flow speeds; flow direction, however, is not affected significantly.

West of the Fairweather fault ice flow velocities in the southern part of the basin are 100 m/yr to 400 m/yr and significantly faster than in the northern part, where the flow is generally less than 100 m/yr. Rapid ice flow along the southern side of the basin deforms rock debris that originates

from cirque glaciers and rock slides into tightly curved and narrow moraine bands that point down slope to the east (Fig. 7-1Supplement).

Ice originating in the western part of the basin flows eastward past an ice-covered topographic rise that extends down the center of the basin, separating more rapidly flowing ice to the south from more slowly flowing ice north of the rise. The two ice streams coalesce within a topographic low just below the rise, where flow is diverted towards the southeast along the splay fault at the terminus of the Fairweather fault (Figure 7). The rise is ≈ 10 km long, up to several km wide, and has ice-surface relief of 25 m – 50 m (Figure 7-2Supplement). En echelon crevasses along the southern side of the rise are presumably developed within a band of high shear strain rate (Fig. 7-1Supplement). This ice-covered rise persists on topographic data sets obtained over a period of years, and the en echelon crevasses are present in Landsat scenes acquired over several decades.

We interpret the rise as the surface expression of an elongated ridge of rock that extends down the center of the basin. Presumably, one or more strands of the Bagley fault lie beneath the stream of rapidly flowing ice that extends beneath the southern side of the basin. Glacial plucking and abrasion of fractured rock within the fault presumably provides a layer of weak, water saturated till within an elongated trough that is excavated into the fault zone. Weak saturated till at the base of glacier enhances rates of flow (e.g. – Boulton and Hindmarsh, 1987).

The structural setting of the northern stream of slower flowing ice is more difficult to interpret. The Columbus fault is mapped along the northern flank of the Bagley Ice Valley and projects

eastward beneath the upper Seward Glacier beneath the northern ice stream (Campbell and Dodds, 1978; Richter et al., 2005). However, when one of us (T.L. Pavlis) visited the fault exposures in 1998, he found that the feature is a compositional boundary separating metamorphic rocks of different lithology rather than a fault. This implies that the northern ice stream may flow along a lithological contact that predates collision of the Yakutat terrane and the rejuvenation of uplift at Mt. Logan (O'Sullivan et al., 1996). Alternatively, the glacier may flow above the outcrop of the reverse-oblique slip fault system that was activated during the M_w 7.4 St. Elias earthquake in 1979, an idea that we explore further.

The St. Elias earthquake initiated on a gently west-northwest dipping thrust fault (Figure 8, fault 1a) at a depth of ≈ 22.4 (± 3) km beneath the mountains north of the eastern Bagley Ice Valley. The rupture then propagated up dip and to the east, initiating slip at a depth of roughly 26 (± 3) km on a dextral-oblique slip fault located beneath Mt. Logan (Figure 8, fault 1b). Rupturing terminated up-dip along the north side of the Bagley fault and immediately west of the terminus of the Fairweather fault (Estabrook et al., 1992). The fault map in Figure 8 is constructed by locating the hypocenters and using fault plane orientations preferred by Estabrook et al. (Table 3, 1992), with the fault surfaces extended upwards to intersect beneath the upper Seward Glacier. Variability in the dip angles and directions of the faults are noted on the figure based on estimates of uncertainty in the earthquake source parameters. We speculate that a third fault (fault surface 1c) links the earthquake source faults 1a and 1b in the subsurface. Key features include: 1) Faults 1a and 1b intersect at a depth of several kilometers near the ice flow divide that separates the Seward Glacier and Bagley Ice Valley. Fault surface 1a is part of the regional de'collement or plate boundary megathrust (Estabrook et al., 1992) and presumably continues

up-dip as part of the Malaspina and perhaps Bancas - Esker Creek faults. 2) Fault 1b abuts the terminus of the Fairweather Fault, providing a structural linkage with the de'collement (fault 1a) to the west as originally proposed by Estabrook et al. (1992). 3) Reactivation of uplift and exhumation at Mount Logan (O'Sullivan et al., 1996) may be driven by reverse motion on faults 1b and/or 1c, which dip northward as 'flower-structure' faults that emanate from the side of the Art Lewis Glacier strike-slip fault zone (Figures 2, 5).

The Bagley fault within the Bagley Ice Valley: The Bagley Ice Valley is divided into eastern and western sections that meet in a topographic saddle above the Bering and Tana Glaciers (Figure 2,3). West of the Tana Glacier the northern flank of the ice valley has undergone younger uplift and exhumation than in the region to the east, and the spatial pattern of exhumation ages suggest that the structure is characterized by uplifted mountain blocks that are bounded on one or more sides by reverse faults (Spotila and Berger, 2008; Berger et al., 2008b). The region west of the Bering and Tana Glacier outlets is also marked by frequent earthquakes with a mixture of reverse and strike-slip focal mechanisms (Figure 4; Doser et al., 2007).

Geology of the ice valley flanks: Mountains that flank the Bagley Ice Valley contain crystalline and sedimentary rocks that were incorporated into the plate margin of southern Alaska prior to collision of the Yakutat microplate (Figure 9; Plafker, 1987; Plafker et al., 1994; Gasser et al., 2011). These rocks were metamorphosed circa 50 Ma, and subsequently thrust over the Yakutat terrane along the Chugach – Saint Elias fault (Figures 1,2). The shallow southern edge of the Chugach – Saint Elias fault was subsequently uplifted and deformed as the Yakutat terrane continued to accrete and deform into a broad foreland fold and thrust belt in the last 10 Ma to 20

Ma. The Bagley fault dips steeply where it cuts through the upper plate of the Chugach – Saint Elias fault (Campbell et al., 1986), presumably penetrates the deeper-seated part of the under-thrust Yakutat terrane, and abuts the de'collement that marks the subduction contact of the crystalline basement of the Yakutat lithosphere (e.g. – Chapman et al., 2008; Meigs et al., 2008; Wallace, 2008; Pavlis et al., under review). The structural configuration of the Bagley fault and underlying subduction thrust is ideal for partitioning oblique plate convergence into strike-slip and thrust-type displacement (e.g. - Haq and Davis, 2010). Structural studies of foreland thrust kinematics by Bruhn et al. (2004) demonstrated that slip along the Chugach – Saint Elias fault and east-trending foreland thrusts was dominantly thrust motion with little or no strike-slip motion.

The steep slopes along the southern flank of the Bagley Ice Valley apparently reflect tectonic uplift that is keeping pace with erosion of the ice valley wall. Topographic relief of the mountains on both sides of the eastern Bagley Ice Valley generally decreases to the west from Mount Logan and Mount Saint Elias, but the southern range flank is generally steeper and higher than the northern flank, consistent with thermochronology data that indicate much younger uplift with greater exhumation of the southern mountain range (Figure 10 C-1, D-1; Berger and Spotila, 2008; Berger et al., 2008b; Enkelmann et al., 2010). Steepness of the mountain flanks above the ice valley is expressed as the average slope index (R/W), which is the ratio of mountain flank relief above the glacier (R) to mountain flank width (W) in Figure 10 (C-2, D-2). The steeper slopes along the southern range flank do not correlate with erosional resistance related to rock composition because the rocks along the northern flank of the ice valley are of equal, and in most areas higher, metamorphic grade than those on the southern flank. The

azimuth or ‘aspect’ of the flank is also poorly correlated with slope angle based on inspection of the topography of other range fronts throughout the region.

Small cirque basins that are elongated north to north-northeast embay the southern flanks of the ice valley (Figure 9). The geometry of the basins is partly if not wholly controlled by the structure of the underlying rock, which is characterized by east-trending folds that are overturned towards the south, and cut by large fracture or ‘joint zones’ that dip steeply and strike north-northeast across the fold axes (Fig. 9-1Supplement). Failure along planar discontinuities in the rock mass created by the structural geology creates rockslides that cascade northwards down the mountain front and onto the glaciers below. This leads to cirque basins that are elongated and point slightly up the topographic slope of the trunk valley glacier instead of normal or down slope as might be expected without a strong control of erosion by rock structure. Rock sliding is very common in this area as evidenced by fresh debris imaged on satellite scenes obtained within the last decade, and by rock sliding events recorded on the Alaska Earthquake Information Center’s seismic network (R. Hansen, personal communication, 2011).

Three linear mountain front segments that are offset by right-handed jogs at the Quintino Sella and Jefferies Glaciers form the northern margin of the eastern Bagley Ice Valley (Figure 9). The ice valley widens from ≈ 5 to 7.5 km on either side of the Quintino Sella Glacier, and then to ≈ 10 km below the Jefferies Glacier. The increased ice flux at the Quintino and Jefferies Glaciers must enhance erosion along the northern mountain flank, causing the valley to widen below each tributary glacier. However, the linear mountain fronts and right-handed jogs are also characteristic of dextral strike-slip fault systems, where the jogs mark pull-apart basins (Aydin

and Nur, 1982). The ice valley is significantly narrower west of the Tana and Bering Glacier outlets, where the northern edge of the western ice valley steps left several kilometers. A left-stepping jog in a dextral fault system is contractional, which fits the structural map prepared by Berger and Spotilla (2008) and Berger et al. (2008b) to account for the younger exhumation ages obtained from the mountain block located on the western side of the Tana Glacier (See Figure 2, 3). One other piece of circumstantial evidence supports the dextral fault interpretation: Several NW-trending glaciated valleys are located within the mountain block between the Jefferies and Tana Glaciers (Figure 9). The longitudinal axis of each valley projects out of the mountain front up and over the Bagley Ice valley as though the head of each valley is truncated by faulting.

The glacier in the eastern Bagley Ice Valley: The topography and dynamics of the glacier in the eastern arm of the Bagley Ice Valley is evaluated the STAR3i DEM (Figure 11) and offset tracking of SAR images (Figure 12) and using ICESat profiles (Figure 13),. The glacier slopes $\leq 1^\circ$ west between its head and the topographic saddle where the eastern and western arms of the Bagley Ice Valley join together (Figures 2, 3). The thickness of the ice is known only near the outlet to the Tana and Bering Glaciers where the ice is 800 m to 1000 m thick and the base of the glacier is near sea level elevation (Conway et al., 2009).

Both persistent and transient features mark the surface of the glacier. Transient topographic features include circular to elliptical hillocks and depressions above migrating englacial fluids, and ‘kinematic waves’ that propagate along the length of the glacier in response to variations in ice flux (e.g. – Lingle et al., 1997; Lingle and Fatland, 2003; Fatland and Lingle, 2002). These transient features are related to ice dynamics and not necessarily direct consequences of bed

topography. Here, we focus on persistent features that reflect ice flow over and around undulations at the base of the glacier. These features exist over decades and are observed on images acquired by different sensors and on elevation models and maps constructed by different techniques.

North to north-northeast ridges and troughs are the most prominent features on the surface of the glacier (Figure 11A). The topographic relief between ridges and troughs is on the order of several decameters, and crest-to-crest spacing varies from roughly 1 km to 10 km (Figure 11B). The ridge crests are curved or sigmoidal in shape, several kilometers long and appear to be laterally offset at several localities (Fig. 11C). Glacier strain rates determined from the ice surface velocity field in Figure 12A also show coincident north-northeast oriented bands of longitudinal contraction downstream of the Jefferies confluence (Fig. 12B), a strain-rate pattern that is expected where ice slows on the up-slope side of a basal ridge and then accelerates over the down-slope side of the ridge (e.g. – Reeh, 1987; Gudmundsson, 2003). The west-northwest facing monocline that extends across the glacier from just below the mouth of the Jefferies Glacier to near the head of the Bering Glacier is exceptional because of its continuity and relatively linear crest (Fig. 11A). These ridges and troughs are relatively stationary in location and persist over decades, thus implying irregular topography at the base of the glacier (Reeh, 1987). The boundary between left-lateral (Fig. 12C, red pattern) and right-lateral (blue pattern) shear is also of interest. Rather than occurring within the center of the glacier, the boundary between the two dextral and sinistral shear strain zones extends along the southern side of the glacier in the eastern ice valley, where the glacier is presumably flowing along an asymmetric valley that is deepest along its southern margin.

448

449 Additional information concerning the morphology of the ice valley is provided by the dynamics
450 of ice flow depicted in Figure 12. The Quintino Sella Glacier flows into the ice valley as the
451 primary ice stream, suggesting that the uppermost section of the Bagley Ice Valley is a hanging
452 valley, forming a subsidiary rather than main trunk glacier flow channel. However, above the
453 confluence, the shear strain rate boundary between left and right lateral shearing remains along
454 the southern side of the ice valley, similar to the situation on the Bagley Glacier below the
455 confluence. Below the confluence with the Jefferies Glacier, the rate of rapid ice flow is also
456 concentrated along the southern side of the ice valley and is then deflected primarily into the
457 head of the Bering, rather than Tana Glacier. Southward curvature of the main trunk channel into
458 the Bering Glacier may reflect deeper erosion where the major fault that lies beneath the Bering
459 Glacier intersects the Bagley fault (Figure 2). Uplift of the mountains and the eastward slope of
460 western arm of the Bagley Ice Valley is driven by movement on the Bering Glacier fault and also
461 by crustal contraction at the left-stepping jog in the northern wall of the Bagley Ice Valley, which
462 occurs across the head of the Tana Glacier. Continuing deformation beneath the western Bagley
463 Ice Valley and surrounding mountains is indicated by a cluster of intense crustal seismicity
464 (Doser et al., 2007), and also by geodetic data which indicates active deformation in this region
465 (Savage and Lisowski, 1986, 1988; Sauber and Molnia, 2004; Elliott, 2011).

466

467 Additional details concerning the elevation of the glacier's surface are provided by ICESat
468 profiles that cross the eastern Bagley Ice Valley between its upper section and the Tana and
469 Bering Glaciers (Figure 13). There is a broad rise or 'bulge' in the ice along the northern side of
470 the glacier in the central area between Mount Saint Elias and Mount Miller, which is not present

on ICESat profiles that cross both higher and lower sections of the valley. The bulge may simply reflect additional snow accumulation along the southern edge of the glacier where the mountain crest is lower between Mount Saint Elias and Mount Miller, providing a pathway for storms to move over the ice valley (Figure 2, 3). However, the bulge is also located where the tectonic highland that is capped by the Guyot and Yahtse Glaciers deforms the Chugach – Saint Elias fault and projects beneath the mountains towards the interior of the eastern Bagley Ice Valley (Figure 2). That is, the north-sloping surface may reflect a structural up-warp beneath the northern side of the glacier.

DISCUSSION

The structure and tectonics of the collisional plate boundary is discussed proceeding from the syntaxis in the east to the terminus of the Bagley fault in the west. We focus on the role of the Bagley fault in accommodating plate boundary motion throughout the history of terrane accretion, followed by a discussion of the seismic potential of the Bagley fault.

Structural geology of Seward Glacier basin: Surprisingly, the most rapid upward advection and exhumation of deeply seated rock (rates up ≈ 7 mm/yr) is located beneath the upper Seward Glacier rather than in the surrounding mountains where the exhumation rates of ≤ 4 mm/yr are significantly less (Enkelmann et al.; 2009). Dilatational strain and splay faulting at the terminus of the Fairweather fault may play an important role in tectonic exhumation by providing a local zone of extension into which rocks are forced by thrust faulting and transpressional strain at depth (Figure 14; Ford et al., 2003). Consider a conceptual experiment, where one squeezes a tube of paste (Bancas - Esker Creek and Malaspina thrust faults driving mechanism – Figure 14),

and removes the lid from the tube (i.e. – the Fairweather extensional splay fault). The paste flows rapidly upwards and out of the tube upon removing the cap. In the case of the upper Seward Glacier, broad tectonic upwelling driven by transpression and thrust-faulting at depth creates the topographic welt encircled by 5000+ m alpine peaks, but the center of the welt is tectonically denuded by crustal dilatation at the end of the Fairweather fault. This process creates the ‘tectonic aneurysm’ where upwelling rock is eroded as quickly as it arrives at the base of the upper Seward Glacier. Sub-glacial rivers that extend beneath the lower Seward and Malaspina Glaciers transport the detritus out of the alpine basin and across the piedmont to the coast as proposed by Enkelmann et al. (2009).

The geometry of the splay fault within the Seward Glacier Basin is consistent with fault growth into a lobe of dilatational strain that develops adjacent to the tip of a strike-slip fault, or ‘mode II’ shear crack in the parlance of fracture mechanics theory (e.g. – Pollard and Segall, 1987). Extensional splay faults or ‘wing cracks’ propagate outward at 70° from the surface of the primary strike-slip fault; the fault in the Seward Glacier basin splays at an angle of $\approx 60^\circ$, consistent with dextral-oblique normal slip in the more complex natural strain field that must exist within the transpressional syntaxis (e.g. – Koons et al., 2010). We also expect to find a zone of intensified contraction along the southern side of the Fairweather fault where the lower Seward Glacier descends the southern range front.

The persistence of the relatively narrow valley of the lower Seward Glacier is puzzling to glaciologists given that the ice flows into the outlet valley at a rate in excess of several hundred m/yr during surging (Figure 7; Headley et al., 2007). Competition between contraction of the

outlet valley by reactivation of the Cascade Glacier fault and widening of the valley by glacier erosion may account for the relatively narrow width given rapid glacier flow which must widen the valley by several millimeters to possibly more than 1 cm each year (e.g. – Hallet, 1979; Headley et al., 2007, also unpublished work by Headley et al., 2012 (see references)). Displacement along the Cascade Glacier fault may constrict the upper part of the outlet valley because it is preferentially oriented for reactivation by thrust faulting within the contractional strain lobe at the Fairweather fault's terminus (Figure 5, 7). This process may be limited to the upper reaches of the glacier valley where the thrust fault is located. At lower elevation the Chaix Hills and Dome Pass thrust faults cross beneath the lower Seward Glacier at a high angle, and these faults are not truncated by younger faulting.

The late stage uplift and exhumation of Mt. Logan within the last 5 Ma presents a fundamental problem when attempting to understand the structural geology of the eastern syntaxis (O'Sullivan et al., 1996; Spotila and Berger, 2008). Geodynamic modeling by Koons et al. (2010) and B.P. Hooks (Ph.D thesis, 2010; personal communication, 2011) predicts a south-dipping reverse fault beneath the northern side of the syntaxis that is conjugate to the Chugach – Saint Elias fault, but this type of structure has not been mapped (Campbell and Dodds, 1982). Either the south-dipping fault does not exist, or it remains to be discovered amongst the ice fields to the north of the Logan Massif.

Alternatively, the uplift of Mount Logan may be driven by displacement on faults 1b and/or 1c (Figure 8) that dip to the northeast and splay off of the Art Lewis Glacier strike-slip fault. The Art Lewis Glacier fault occupies a linear ice filled valley that branches off of the Fairweather

fault and extends around the northeastern side of Mount Logan (Figure 2, 4). The proposed structure is a one-sided flower structure where transpression is accommodated by a linked strike-slip and thrust fault system. Similar ‘one-sided’ transpressional structures occur elsewhere at the structural transition into the eastern syntaxis. One-side flower structures include the Hubbard Glacier thrust – Art Lewis Glacier fault pair northeast of Disenchantment Fjord, and the Yakutat thrust – Fairweather fault system in Russell Fjord and the coastal mountains (Figure 5, also see Bruhn et al., 2004).

Evidence for strike slip faulting in the Bagley Ice Valley: Our interpretations of faulting beneath the eastern Bagley Glacier are based on several observations:

(1) Topographic features at a glacier’s base perturb the surface of the ice where they appear as ‘muted’ undulations that persist over time (Fowler, 1982; Gudmundsson, 2003). The surface undulations may change in wavelength and amplitude and shift laterally by a limited amount because of temporal fluctuations in ice velocity, but the features persist on the surface of the glacier over decades.

(2) Valley glaciers erode the bedrock into a repetitive series of steep down-glacier facing steps (cliffs) that are separated by longer tracts of abraded and till-mantled bedrock that slope gently either down or up-valley; e.g. large scale ‘roche moutonnee’ landforms in de-glaciated terrain (Figure 15A; Hooke, 1991). Cliffs are created by ice plucking out the bedrock as it flows down slope, and the intervening treads are created where the debris-laden ice abrades the underlying bedrock. When this ‘step and tread’ topography is offset by strike-slip faulting at the base of the

glacier the surface of the glacier will develop low-amplitude ridges and swales that are truncated along their axes (Figure 15B, C).

(3) Large strike-slip fault zones are characterized by distinctive patterns of subsidiary faulting and related topography (Tchalenko, 1970). Pull-apart basins and thrust-faulted ridges form at jogs and bends within the fault zone, and subsidiary strike slip faults are inclined to the regional boundaries of the fault zone (Tchalenko, 1970). These subsidiary faults are clearly displayed in arid landscapes where rates of tectonic activity outpace erosion, but beneath temperate glaciers the smaller-scale features may be quickly removed by erosion, or mantled by till. Pull-apart basins and large thrust-faulted ridges that form at jogs and bends in a strike slip fault system persist because of greater original topographic relief compared to lower-relief features developed by lateral displacement along strike-slip faults.

Features that may be partly preserved structures associated with dextral faulting along the northern edge of the Bagley Glacier include pull-apart depressions at the right-stepping jogs where the Quintino Sella and Jefferies Glaciers enter the ice valley. Contractional jogs and bends occur 1) where the northern margin of the Bagley Ice Valley steps several kilometers south (left-handed step) across the head of the Tana Glacier, and 2) where the Bagley and Martin River Glacier faults join in a restraining fault bend (Figure 2). Some dextral shearing along the Bagley fault extends at least 40 km west of this latter restraining bend, where the fault lies beneath the linear Miles Glacier. The 4 km offset of the mountain front where the Miles Glacier enters the Copper River indicates dextral shearing, and the pattern of rock exhumation ages reflects uplift along the southern side of the fault (e.g. – Berger et al., 2008).

586

587 We interpret the low-amplitude sigmoidal ridges on the surface of the eastern Bagley Glacier as
588 a subdued topographic expression of dextrally faulted ‘step and tread glacier valley’ topography
589 at the base of the glacier (Figure 11, 15). The sigmoidal shape of the ridges reflects erosional
590 smoothing of the bedrock and possibly clock-wise rotations of the faulted blocks in the dextral
591 shear zone. Longitudinal ice strain rates derived from Bagley Glacier flow velocity data confirm
592 the presence of north-northeast elongated ridges at the glacier’s base (Figure 12B). The large
593 northwest-facing monoclinal flexure on the surface of the glacier located just below the inlet of
594 the Jefferies tributary glacier may reflect the presence of a large reverse- fault cored fold that
595 trends obliquely across the dextral shear zone at the base of the Bagley Glacier.

596

597 Uplift along the southern side of the Bagley fault is required during the last several Ma based
598 upon the results of regional thermochronology studies that indicate much younger uplift and
599 exhumation along the southern sides of the fault zone between Mount Saint Elias and the Bering
600 Glacier, and also along the southern side of the Miles Glacier (e.g. – Berger and Spotila, 2008;
601 Berger et al., 2008a,b; Spotila and Berger, 2008). The region between the western Bagley Ice
602 Valley and Martin River fault system has been uplifted and exhumed over a broader area,
603 including the mountains on both the northern and southern side of the Bagley fault. Hypotheses
604 concerning the structure responsible for uplift of the southern mountain flanks include a south-
605 dipping reverse fault (Berger and Spotila, 2008; Chapman et al., 2008; Wallace, 2008), up-
606 warping of the mountains where active east-northeast trending foreland thrust faults project
607 beneath the mountains along the southern edge of the Bagley Ice Valley (Enkelmann et al.,
608 2010), and uplift and ‘back-rotation’ of the entire mountain block above a north-dipping fault

ramp that connects foreland thrusts to the subduction zone beneath southern Alaska (Pavlis et al., under review).

Although our work on the Bagley fault and the geomorphology of its mountain flanks does not distinguish between the various hypotheses for uplift along the southern side of the Bagley Ice Valley, we note that the southern flank of the eastern ice valley is steep and embayed by a number of small cirque basins. This suggests that the southern flank is rejuvenated by tectonic activity rather than an old mountain front that is worn down by erosion. The most likely locus of reverse faulting is along the southern side of the Seward Glacier Basin and eastern Bagley Ice Valley, where the glaciers flow most rapidly leading us to infer the presence of a linear fault strand at depth. In this scenario, Pliocene and younger deformation is partitioned between dextral shearing beneath the central and northern edge of the ice valley, and uplift by reverse faulting along the southern edge. We postulate that the more complex pattern of deformation and uplift surrounding the western part of the Bagley fault is related to the 1) the intersection of the Bering Glacier fault, 2) crustal contraction and ‘pop-up’ mountain blocks created by the left-stepping fault jog in the northern wall where the Tana Glacier exits the ice valley (Beger et al., 2008b), and 3) the restraining bend formed where the Bagley and Martin River Glacier faults meet (Figure 2). This region is also one of the most seismically active areas within the Saint Elias orogen, which is consistent with this conclusion (Figure 4; Doser et al., 2007).

Role of Bagley Fault in plate boundary deformation: Our analysis of remote sensing and geological data provides a better foundation for integrating the Bagley fault into the tectonic framework of the Saint Elias orogen. Structurally, the configuration of the plate boundary created

by the fold-thrust belt thrust and the Bagley faults is ideal to partition oblique plate convergence into thrust and strike-slip motion (Bruhn et al., 2004; Haq and Davis, 2010). Bruhn et al. (2004) specifically searched for evidence of oblique thrust faulting versus plate boundary slip-partitioning during their structural study of the Chugach – Saint Elias fault and older foreland thrust faults in the central part of the Saint Elias orogen. We concluded that the requisite strike-slip motion was accommodated along the Bagley fault rather than by oblique thrust faulting (they used old Contact fault terminology) prior to the eastward step of the megathrust de'collement from the Kayak Island zone to the Pamplona and Malaspina faults sometime during the Pliocene to early Quaternary. Subsequent work has shown that the Bagley fault remained active since the Pliocene (e.g. – Berger and Spotila, 2008; Chapman et al., 2008; Spotila and Berger, 2008), although vertical motion may have become most important as the leading edge of subduction migrated ≈ 200 km eastward (e.g. – Bruhn et al., 2004; Worthington et al., 2011). Doser et al. (2007) speculate that a linear south-dipping band of earthquakes beneath the mountains on the south side of the Bagley Ice Valley may mark the reverse fault first proposed by Berger and Spotila (2008).

Cumulative strike-slip motion along the Bagley fault is difficult to resolve because there are no unambiguous piercing points to match on either side of the fault zone. Restoring the sliver of the relict plate boundary preserved at Ragged Mountain back to a location near the head of the Martin River Glacier requires roughly 50 km of dextral shearing along the Martin River and Bagley faults (Figure 16). It is interesting, albeit speculative, to note that this restoration aligns the several northwest trending glacier-filled valleys in the mountains along the southeastern side of the Steller Glacier with the 'headless' valleys located on the northern side of the Bagley Ice

Valley between the Jefferies and Tana Glaciers (Figure 16, inset image). This restored valley alignment could simply be fortuitous given that glaciation can reset the landscape within a period of a few hundred thousand years, but it is not outrageous given the long and protracted history of oblique convergence along the plate boundary (Plafker et al., 1994).

Seismic potential of the Bagley fault: Estabrook et al. (1992) noted that the Bagley fault is at the very least an important structural and mechanical boundary in the orogen. The Bagley fault blocked up-dip rupture propagation on faults 1a and 1b (Figure 8) during the M_w 7.4 Saint Elias earthquake, and also bounded an offset or step in the hypocenter depths of aftershocks. We add that the Bagley fault also marks the terminus of several active thrust faults that cut across the foreland of the Yakutat microplate and project beneath the western Seward Glacier basin and Bagley Ice Valley (Figure 2, 17).

Although recent geodetic results across the Bagley Ice Valley suggest minimal strain accumulation rates (Elliott, 2011), there is a strong rationale for considering the Bagley fault capable of generating earthquakes. The fault is structurally linked to major seismogenic faults in the orogen (Figure 17), it is marked by both diffuse and spatially clustered seismicity with focal mechanisms that indicate dextral shearing in some areas, but more complex deformation with both normal and reverse faulting in others (Figure 4; Doser et al., 2007; Ruppert, 2008), and the fault is favorably oriented for reactivation in the contemporary stress field (e.g. – see regional stress map of Ruppert, 2008). The fault is capable of generating $M_w \leq 7.5$ earthquakes were it to rupture along the 125 km long section extending between the upper Seward and Bering Glaciers according to earthquake moment magnitude versus surface rupture length equations of

Wells and Coppersmith (1994). This section of the fault zone is relatively linear and bounded by clusters of earthquake activity where the Malaspina and Bering Glacier foreland thrust faults project towards and intersect the Bagley fault at depth. Admittedly, the fault is a complex structural zone that contains several strike-slip and presumably one or more reverse fault strands that may rupture independently to generate small to modest magnitude earthquakes, or alternatively, link together to form a complex seismic source zone for larger earthquakes.

CONCLUSIONS

- 1) The Bagley fault is a profound mechanical and structural boundary within the crust of the southern Alaskan plate margin that is linked to the Fairweather transform fault at its eastern end and to the Martin River Glacier fault to the west. The fault bounds the northeastern ends of crustal thrust faults that extend through the interior of the Yakutat terrane and beneath the southern most edge of the Alaskan plate margin. As noted by Estabrook et al. (1992) the Bagley fault also limited the spread of fault rupturing during the Saint Elias earthquake (M_w 7.4, 1979) and marked a boundary separating domains of different hypocentral depths for aftershocks.
- 2) Rapid uplift and exhumation surrounding the Seward Glacier is caused by crustal contraction related to thrust faulting and transpressional strain beneath the mountains and localized extension high in the crust surrounding the terminus of the Fairweather transform fault. Evidence for dextral shearing along the Bagley fault includes a series of NNE-trending ridges and swales on the surface of the Bagley Glacier that are offset in a dextral sense and right-handed jogs in the northern wall of the eastern Bagley Ice Valley at the Quintino Sella and Jefferies Glaciers. A tentative correlation of NW-trending

valleys that are truncated by the Bagley fault indicates 50 km of dextral displacement, which is probably a minimum value.

3) The Bagley fault has a protracted history of deformation caused by collision of the Yakutat microplate. This includes both dextral shearing as part of the slip-partitioned plate margin, and vertical uplift of the mountains along the southern side of the Bagley Ice Valley. The vertical component of motion was presumably enhanced during the last $\approx$ 5 Ma when the subduction front migrated eastward to its present position near the eastern syntaxis, partly by-passing the slip-partitioned and structurally linked Chugach – Saint Elias – Bagley Fault system.

4) The Bagley fault is considered active and a potential earthquake source because it is directly linked to strike-slip and thrust faults that have undergone Quaternary displacements and generated historical earthquakes. The largest earthquake of $M \leq 7.5$ may occur on the section of fault zone between the upper Seward and Bering Glaciers, which is demarcated by clusters of earthquake activity at its ends.

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724 **Figure Captions**

725

726 Figure 1: Plate tectonic setting of southern Alaska and offshore Gulf of Alaska. The Yakutat
727 microplate is labeled and shaded in tan. CSEF = Chugach Saint Elias fault is the suture between
728 rocks of the Yakutat microplate or ‘terrane’ and southern Alaska. DF = Deformation Front is the
729 hypothesized eastern most limit of subduction of the basement or crystalline rocks of the Yakutat
730 microplate. Major plate boundaries in addition to CSEF and DF are the Fairweather – Queen
731 Charlotte fault, the Transition fault and the Aleutian megathrust. The region of Figure 2 is
732 outlined in the red dashed rectangle.

733

734 Figure 2: Fault map of the Saint Elias orogen superimposed on a MODIS (Moderate Resolution
735 Imaging Spectroradiometer) image background. See dashed red rectangle in Figure 1 for
736 location. Faults with incontrovertible evidence for Late Pleistocene and younger displacement
737 are shown in red. Those faults that are suspected to have been active, or at least partially
738 reactivated, during the same time period are shown in purple. The orogen is divided into three
739 segments, an eastern segment marked by the Fairweather transform fault and coastal mountains
740 thrust and fold belt, a central segment containing the Chugach – Saint Elias fault suture and

broad foreland fold and thrust belt, and a western segment where the Yakutat terrane is molded into the syntaxis of southern Alaska at the northeastern end of the Aleutian megathrust. Onshore faults are located primarily from mapping by Plafker (1987); Bruhn et al. (2004); Chapman et al. (2008), and Chapman et al. (2012). Offshore structures are located from marine geophysical surveying reported by Worthington et al. (2008; 2011). Fault numbers are as given in Tables 1A and 1B.

Figure 3: Topographic profiles of the northern (A) and southern (B) mountain crests bordering the Bagley fault along the length of the Saint Elias and Eastern Chugach Mountains. Rock exhumation ages are marked in red and based on published results by Berger and Spotila (2008), Spotila and Berger (2008), Berger et al. (2008a, 2008b); Enkelmann et al. (2009; 2010), and O'Sullivan et al. (1996). The blue line marks the surface elevation along the centerline of the glaciers. Notice that the rock exhumation ages are older along the northern side of the Bagley Ice Valley than along the southern side, and that this pattern also applies to the region of the Miles Glacier west of Mt. Tom White. See Figure 2 for locations of major geographic features. Elevation data are from the ASTER GDEM global elevation model.

Figure 4.: Earthquake epicenters ($M \geq 1.5$) and first motion focal mechanisms ($M \geq 2.5$)-from Alaska Earthquake Information Center earthquake catalog (July, 2005 - June, 2011, depth ≤ 30 km). In 2005 and 2006 22 new seismic monitoring sites were installed in the St. Elias Mountains region as part of the STEEP project (Saint Elias Erosion and Tectonics Project). Addition of these sites to the existing seismic network greatly expanded monitoring capabilities in the region in terms of accuracy of earthquake locations and source mechanisms. Location errors depend on the

size and location of an earthquake. Typically, larger events have more and clearer arrivals, therefore resulting in better quality locations with smaller errors. In the STEEP network core area, best-located events ($M \geq 2$) have errors on the order of 2-3 km or less. Note: There are two major regions with high background seismicity; one in the Icy Bay/Malaspina region and the other west of Bering Glacier. These regions of higher background seismicity have been observed over the last several decades, even prior to the 1979 Saint Elias earthquake. Double couple focal mechanisms contain two possible fault planes oriented normal to one another; of which one is the actual fault. Keeping this ambiguity in mind, there are mechanisms consistent with dextral shearing along or near the Art Lewis Glacier and Fairweather faults, at the eastern end of the Bagley fault in the upper Seward Glacier Basin, along the western part of the Bagley fault, including one event near the intersection of the Bagley and Martin River (Glacier) faults, and at the southwestern end of the Martin River fault. Note two normal faulting events beneath the western Bagley Ice Valley and near the intersection of the Bagley and Martin River faults. Focal mechanisms in the foreland of the orogen indicate a mixture of thrust and strike-slip fault motion, with only a few normal faulting events.

Figure 5: Shaded relief image viewed towards the west of the structural syntaxis formed at the transition from strike-slip to intense transpression along the plate boundary in the central segment of the orogen. This transition is marked by two bends in the plate boundary. The boundary first bends westward at Disenchantment Fjord where the terrain rises abruptly to the west. The second and more prominent bend is located beneath the upper Seward Glacier where the plate boundary rotates an additional 25° west along the Chugach – Saint Elias and Bagley

787 faults. The shaded relief image is created from the ASTER Global Digital Elevation Model
788 (GDEM). Refer to Figure 2 for locations of major geographic and structural features depicted in
789 this scene.

790
791 Figure 6: Topographic map of the Hubbard and Valerie Glaciers showing the concealed traces of
792 the Fairweather (Pt. B) and Fairweather Boundary faults. Notable features include (1) the south-
793 facing cliff (A) at the confluence of the Valerie and Hubbard glaciers created by dextral
794 displacement of ≈ 2.5 km along the Fairweather fault (Stars 1 – 2), (2) 4.5 km dextral offset of
795 the mountain front by displacement on the Fairweather fault between stars 1 and 3, and (3) a
796 monoclinical flexure on the surface of the Hubbard Glacier formed by a NE-dipping thrust fault
797 (Pt. C) that presumably intersects the Art Lewis Glacier fault at depth. The topography is from
798 Shuttle Radar Topographic Mission (SRTM) data.

799
800 Figure 6-1Supplement: Oblique view of the Fairweather fault where it lies beneath the trough of
801 the Valerie Glacier. The figure illustrates the contractional bend in the fault trace where there is a
802 ‘pop-up’ ridge between 970 m and 1827 m. Note also that the active trace of the fault is located
803 along the southern margin of the glacier valley, a common characteristic of large strike-slip fault
804 zones. The fault terminates beneath the upper Seward Glacier in a northwest trending splay fault
805 that we interpret to be partly extensional. The Cascade Glacier thrust may also be partly
806 reactivated by enhanced contractional strain on the opposite side of the Fairweather termination,
807 acting to partially close the outlet valley to the lower Seward Glacier which feeds the Malaspina
808 Glacier on the piedmont.

Figure 7: **A.** Velocity of ice flow measured on the surface of the upper Seward Glacier by optical tracking of offset features using two Landsat images acquired one year apart. The small arrows indicate direction and velocity of ice flow at points on a grid where the optical tracking algorithm is able to resolve displacement on the surface of the glacier. The thick blue lines with arrowheads represent generalized direction of flow in various parts of the basin summarized from the underlying optical tracking vectors. A subtle topographic welt or rise affects flow near the center of the glacier (7B). **B.** Close up of the ice velocity field shown in 7A (dashed rectangle) focusing on the areas surrounding the ice-covered ridge of bedrock that affects ice flow in the western part of the basin (Also see electronic supplement figures 7-1Supplement and 7-2Supplement that show more details of deformed moraine bands and crevasses and several topographic profiles across the glacier's basin).

Figure 7-1Supplement: Binary black – white segmentation image of a Landsat scene showing ice crevassing and flow-deformed traces of moraine on the surface of the upper Seward Glacier. Note en echelon crevasses along the southern flank of the ice-covered ridge of bedrock that is outlined in the dashed brown polygon. Red polygons are outcrops of bedrock that poke through the snow and ice on the southern and northern flanks of the basin. The image is derived from a Landsat scene with bedrock mapped by Band 7. The binary black – white image is constructed by segmentation of a false color composite image created with Bands 7,4,1. Refer to Figure 6 for location of the image by comparing geographic features listed in each figure. The location of the figure is also indicated in UTM coordinates that are marked around it borders.

Figure 7-2Supplement: Three topographic profiles across the basin of the upper Seward Glacier extracted from ICESat laser profiling tracks. Track locations are shown in the satellite image in the upper right corner of the figure, with the profiles marked in black on each track. The location of a high-resolution laser data swath (ATM) that was used to verify features in the Figure 7-1 supplement and the ATM profile is marked in purpleTrack 051 crosses the upper part of the basin just below the topographic divide at the head of the eastern Bagley Ice Valley, tracks 163 and 029 cross the central and lower parts of the western section of the basin, where the ice covered ridge of bedrock (Fig. 7B) creates an elongated east-trending rise that extends down the center of the basin.

Figure 8: Shaded relief map of the Saint Elias Mountains showing the mapped projections of faults 1a and 1b that ruptured during the M_w 7.4 Saint Elias earthquake in 1979 (Estabrook et al., 1992). The main shock of the Saint Elias earthquake nucleated at the large red star in the northwest corner of fault 1a and the ruptured up-dip towards the Bagley Fault and along strike to the east, where rupturing then spread onto fault surface 1b. The aftershock zone of the 1979 earthquake spread southward from beneath the main range into the foreland beneath the Malaspina Glacier and Icy Bay (shaded orange shape). Fault 1b projects upwards towards the east-west trending ridge of bedrock (brown rectangle) that affects ice flow in the western part of the Seward Glacier basin (Fig. 7).

Figure 9: Topography and geology of the eastern Bagley Ice Valley and western part of the Seward Glacier basin. Glaciers are in gray scale and rocks are color-coded to demarcate units on the geologic map of Wrangell – Saint Elias Park and Preserve (Richter et al., 2005). The rose

diagram shows the trends of cirque basins along the southern flank of the Bagley Ice Valley, with the number of observations keyed to the lengths of each petal. There are a total of $n = 20$ measurements on the plot. Topographic contours and the shaded-relief base map are constructed from the STAR3i DEM (Intermap Technologies, 1996). The dashed yellow rectangle is the location of the structural study area presented in Figure 9-1Supplement.

Figure 9-1Supplement: Relationships between geologic structure, rock sliding and the origin and shaping of cirque basins along the southern flank of the eastern Bagley Ice Valley. **A.** Oblique view of part of the southern flank with prominent structural surfaces or ‘rock mass discontinuities’ labeled on the figure. **B.** Lower hemisphere stereographic projection showing poles to bedding on fold limbs (Point clusters P1 and P2) and joints (cluster P3) within the rock mass. S1, S2 and S3 are the corresponding great circles to the average poles to bedding and joints. There is also a foliation that is axial planar to the folded bedding, and that dips to the north. Foliation and bedding strikes sub-parallel to the trend of the ice valley, and axial surfaces of folds dip steeply towards the north. Joint set S3 intersects the foliation and bedding surfaces and cuts across the axial surfaces of the folds. Mass wasting by rock sliding is caused by failure along the north dipping foliation and bedding surfaces with joint set S3 providing the discontinuities that limit the lateral extent of slide masses. Topography and structural surfaces were extracted from the STAR3i DEM with the strike and dip of prominent structural surfaces determined by three-point solutions and field reconnaissance.

Figure 10: **A.** Perspective view of the eastern Bagley Ice Valley and Seward Glacier Basin

created by draping a false color Landsat scene (Bands 5,4,1) over the ASTER GDEM. Note that the eastern Bagley Ice Valley slopes westward, and the western part of the ice valley slopes to the east. Ice flowing from both sections of the ice valley feed the Bering and Tana glaciers, with the preponderance of ice flowing into the Bering Glacier. **B.** Schematic illustration of the mountainside relief (R) to width (W) geomorphic index, and symbols for thermochronology dates summarized by Enkelmann et al. (2010). The colored symbols indicate the age at which bedrock samples passed below the thermal closing temperature (T_c) for apatite and zircon. Approximate closing temperatures associated with various minerals and methods are: 1) apatite - ap He ($U-Th/He$) = $60^{\circ}C$, 2) apatite fission track (ap FT) = $110^{\circ}C$, and 3) zircon fission track (Zr FT) = $250^{\circ}C$. C and D: Plots of the ridge line topography on the north (C1) and south (D1) sides of the eastern Bagley Ice Valley, with associated plots of the geomorphic ratio R/W for each mountainside (C2, D2), respectively. R/W is greater on the north-facing mountainside leading up to the southern ridgeline than on the south-facing mountainside leading to the northern ridgeline. The surface of the glacier is shown as a blue dashed line on both C1 and D1 plots. Locations of bedrock samples collected for thermochronology analyses are indicated on profiles in C1 and D1, with the age color coded as indicated in part B. In general, dates at which the temperature of bedrock samples passed below T_c are younger on the southern side of the Bagley Ice Valley compared to the northern side (Enkelmann et al., 2010).

Figure 11: **A.** Shaded relief image of the residual topography on the surface of the eastern Bagley Ice Valley created by removing the regional surface slope on the glacier. **B.** Longitudinal profile along the center of the eastern Bagley Ice Valley showing the residual topography. Note that ridges with relief several tens of meters are separated by several kilometers. **C.** Interpretation of

the style of faulting at the base of the glacier that may cause the apparent offset in the surface topography (ridge crests) of the shaded relief image in A. The red dashed line denotes the inferred location of a major dextral fault at the base of the glacier, and the asterisks mark locations where the ridges are offset in a dextral sense. Note that we infer dextral faulting of stair-step like topography formed by erosion at the glacier's base, as sketched in Figure 15.

Figure 12: Ice velocity and strain rate on the Bagley Icy Valley determined by SAR offset tracking using normalized cross correlation (GAMMA Software, (Strozzi et al., 2002)) on two image pairs acquired between January and April, 2010. **A.** Glacier flow velocity field, speed indicated by color bar. **B.** Glacier ice strain rates in the direction of ice flow. **C.** Glacier ice shear strain rates showing vorticity or magnitude of the rotational component of the shear strain rate tensor.

Figure 13: Topographic profiles across the eastern Bagley Ice Valley extracted from ICESat tracks (A) 1279 and (B) 416 (See Fig. 9 for locations). Note that the southern side of the glacier is higher than the northern side possibly because of uplift at the base of the glacier where the tectonic highland that is capped by the Guyot and Yahtse Glaciers extends beneath the southern flank of the ice valley.

Figure 14: Alternative structural models for deformation in the basin of the Upper Seward Glacier. **A.** Prominent paths of ice flow (blue arrows) and locations of faults within the basin. Panels B through C show views of the basin with the south side cut away to illustrate locations of faults and the alternative models for fault interactions and activity. Fault 1b is projected to the

surface based upon the earthquake rupture model of Estabrook et al. (1992) (see Fig. 8). The location of the bedrock ridge in the western part of the basin (Fig. 7) is marked by the white-hatch line crevasse pattern. **B.** East-west schematic section showing how the effects of bending moment stresses created by uplift and bending of the mountain block above the Malaspina and Esker Creek faults may contribute to extension on the NW-trending splay fault at the terminus of the Fairweather fault. Extension at the end of the Fairweather fault with subjacent contraction on the thrust faults will drive material up from depth into the basin – a process that may explain the rapid upwelling of rocks (≈ 7 mm/yr) proposed by Enkelmann et al. (2009). Bancas Point is located on the north-shore of Disenchantment fjord. **C.** Only active faulting in this scenario is at the terminus of the Fairweather Fault, which last ruptured into the basin during the M 7.9 earthquake in 1959 (Doser, 2010). In this scenario the upper part of fault 1b (Fig. 8) either does not crop out at the base of the basin and/or the bedrock ridge marked by the en echelon crevasses is solely the result of erosion. The Bagley fault is also inactive. **D.** All faults are active with fault 1b (Fig. 8) cropping out beneath the en echelon crevasse field in the center of the basin, and the motion on the Bagley fault uplifts the southern mountain wall relative to the basin. Motion on the Bagley fault is mostly convergent with a modest amount of dextral shearing compared to that on the Fairweather fault. If topographic and bending moment stresses created above the Malaspina and Esker Creek faults overwhelm the horizontal contraction across the basin, then the Bagley fault may become an oblique-slip normal fault.

Figure 15: **A.** Sketch of the step and tread topography that evolves by erosion at the base of valley glaciers (Hooke, 1993). **B.** Illustration of offset in the step and tread topography caused by dextral strike-slip faulting. **C.** Map view of part of the shaded relief image of residual topography

on the surface of the lower Bagley Ice Valley in Figure 14. The white stars mark locations where the surface morphology suggests dextral offset of step and tread bedrock topography at the base of the glacier.. The illumination angle is from an azimuth of 150° and elevation of 20° . Southeast facing slopes are lighter and northwest facing slopes are darker gray-scale.

Figure 16: Landsat V false color image of the west-central and western part of the Saint Elias orogen showing part of the foreland fold and thrust belt east of the Bering Glacier, and the multiple-phase deformed region of tectonic accretion and extrusion in the structural syntaxis west of the Bering Glacier. The two red dashed rectangles enclose remnants of NW-tending valleys that may have once been continuous across the Bagley Fault. Restoration of the valleys by removing 50 km of dextral slip along the Bagley Fault is illustrated in the lower right part of the figure with each valley marked by a dashed line with arrowhead pointing down-valley. Ragged Mount (RM) is a deformed sliver of the Alaskan plate margin that has been carried to the west and south by motion on the Bagley Fault. We restored Ragged Mountain to a position near the head of the Martin River Glacier from its present position (RM) through intermediate positions (RM2 -> RM1) by removing 50 km of dextral displacement on the Bagley Fault. Note that locality RMo places Ragged Mountain adjacent to Mount Tom White and the upper Steller Glacier. The prominent peak of Mount Tom White rises abruptly from the restraining bend where the Bagley Fault links to the Martin River Glacier fault. Dashed black lines marked 1279 and 416 locate the ICESat profiles shown in Figure 13.

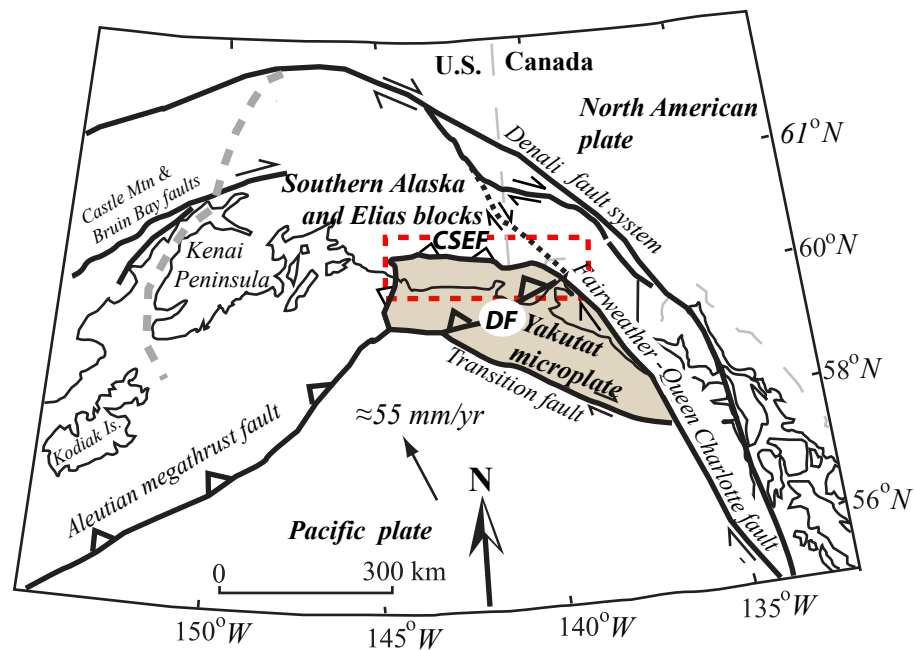
Figure 17: Preliminary three-dimensional model of tectonically active faults in the Saint Elias orogen and their geometrical relationship to the Bagley fault, which is modeled as a vertical

971 surface. The locations of the faults are shown in Figure 2. The strikes and dips of the faults are
972 taken from the references noted in Table 1a and 1b. Note that the Bagley fault lies in the hanging
973 wall of the megathrust de'collement that accommodates subduction of the crystalline basement
974 (crust and upper mantle) of the Yakutat microplate. The other faults are large imbricate thrust
975 faults, or major strike slip faults (e.g. - Fairweather, Art Lewis Glacier, and Martin River faults)

Figure 1

[Click here to download Figure: Figure1.pdf](#)

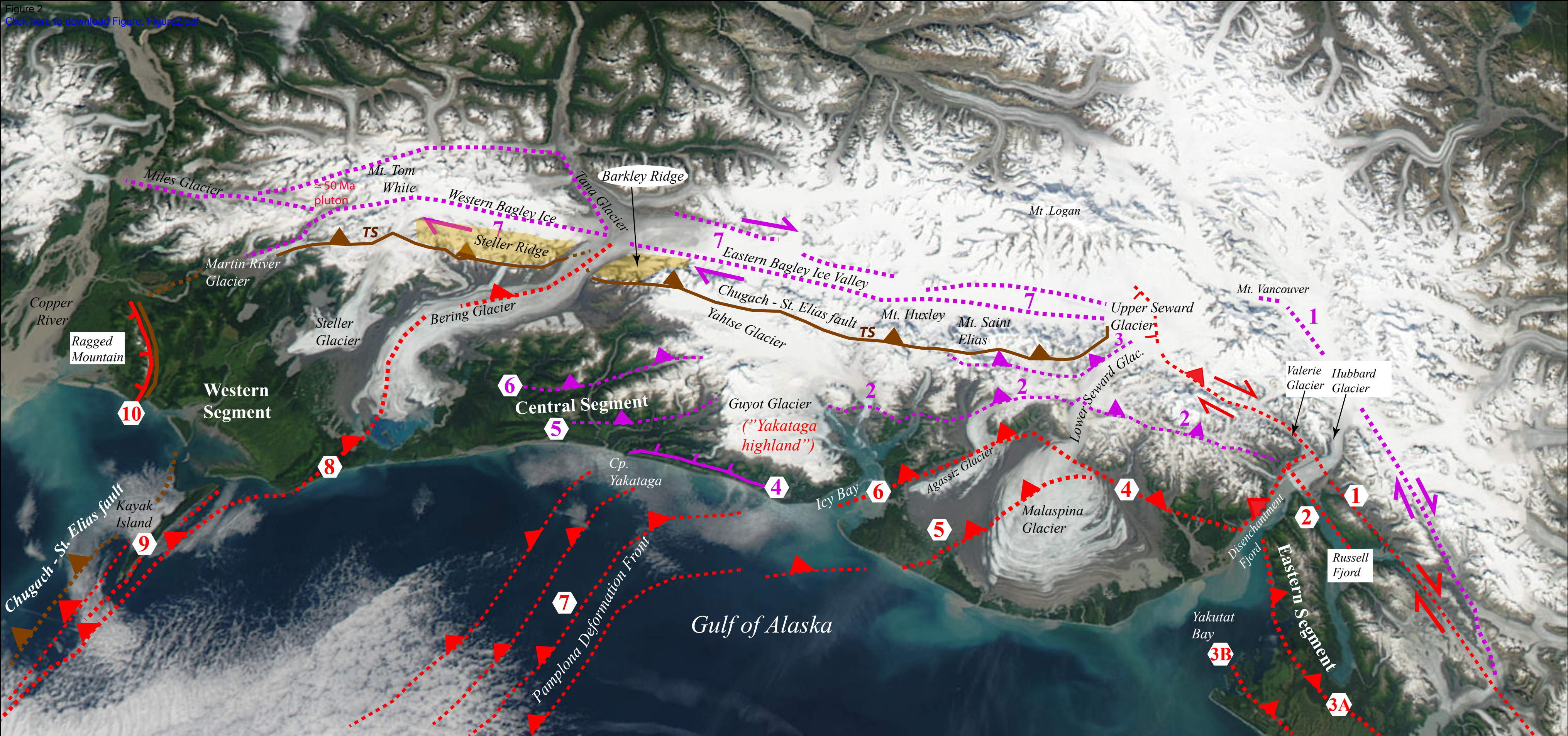
Figure 1, Bruhn et al.



CSEF - Chugach - Saint Elias fault.

DF - Eastern edge of deformation associated with decollement-style faulting and folding in the Yakutat microplate. Includes the Pamplona thrust faults on the continental shelf, and the Malapina fault system on land.

Figure 2
[Click here to download Figure: Figure2.pdf](#)



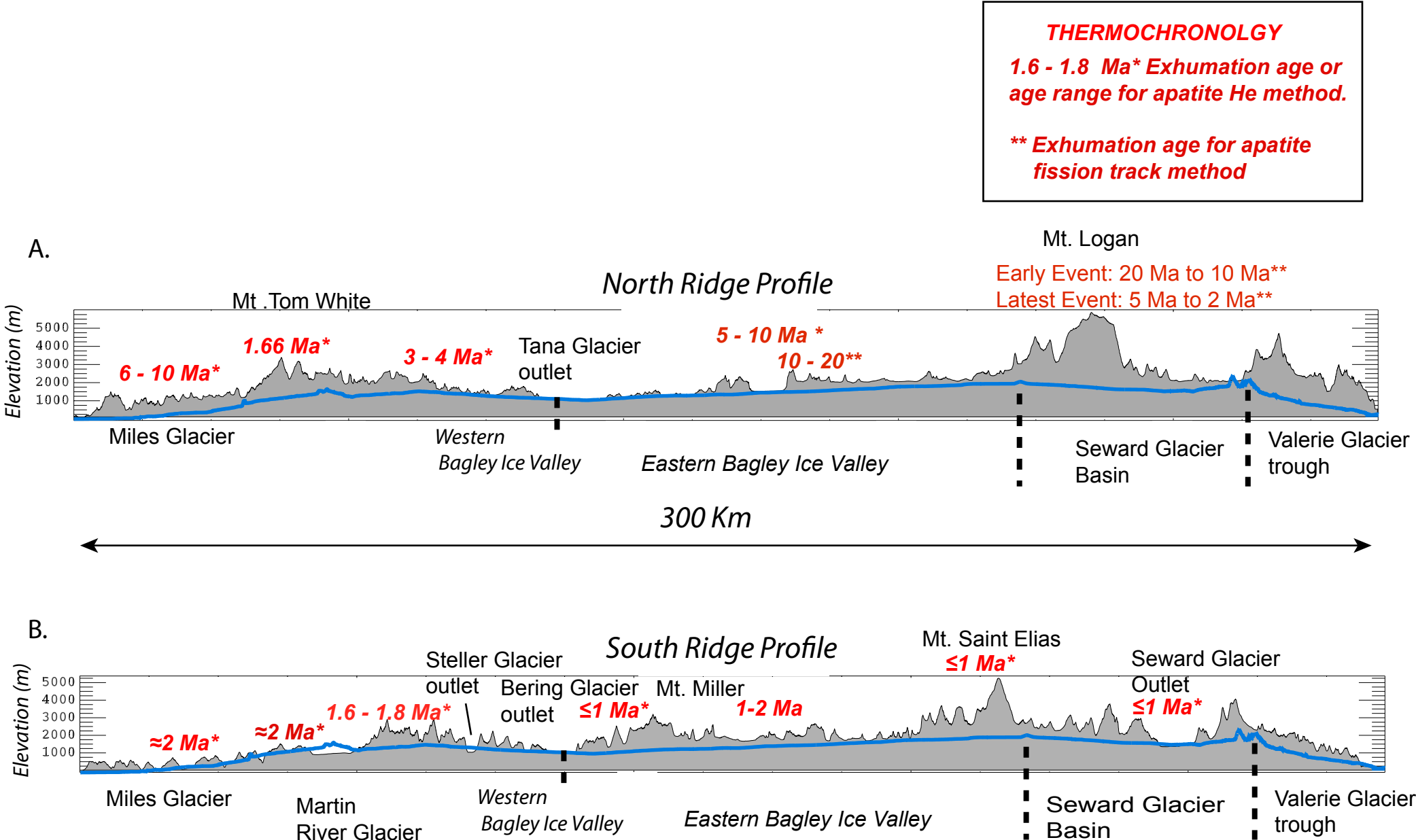


Figure 4
[Click here to download Figure: Figure4.pdf](#)

Figure 4, Bruhn et al.

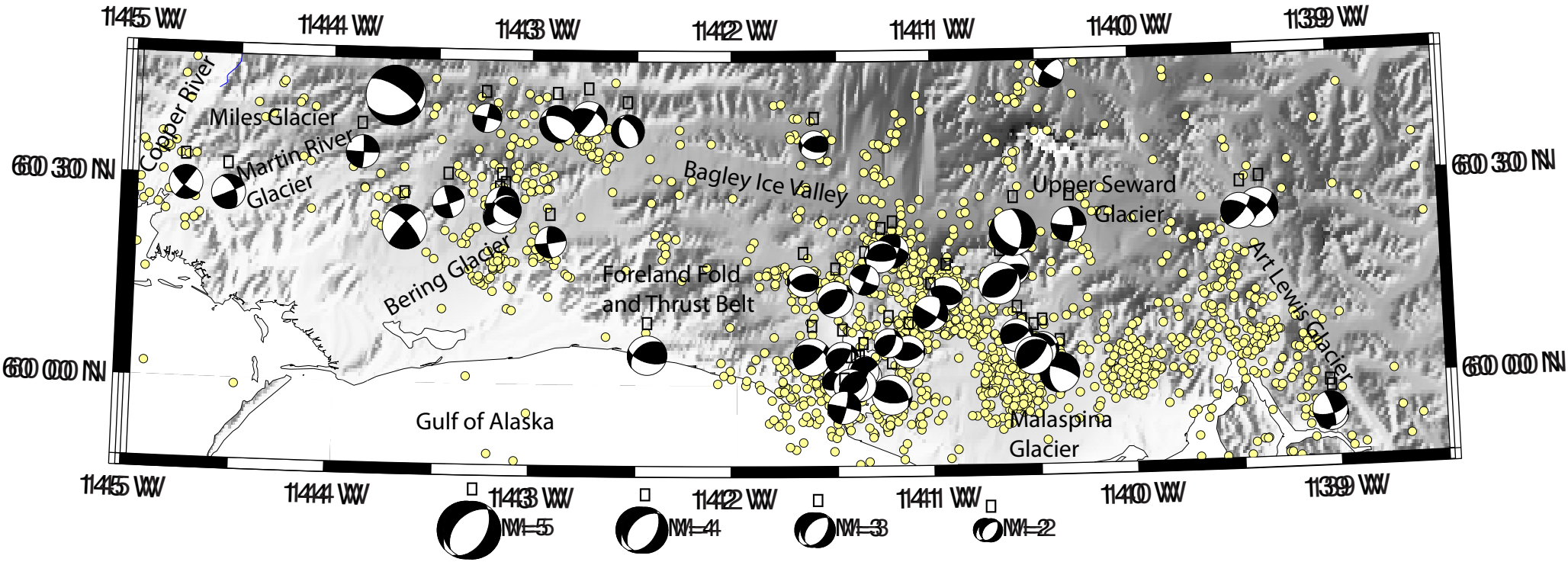


Figure 5

[Click here to download Figure: Figure5.pdf](#)

Figure 5: Bruhn et al.

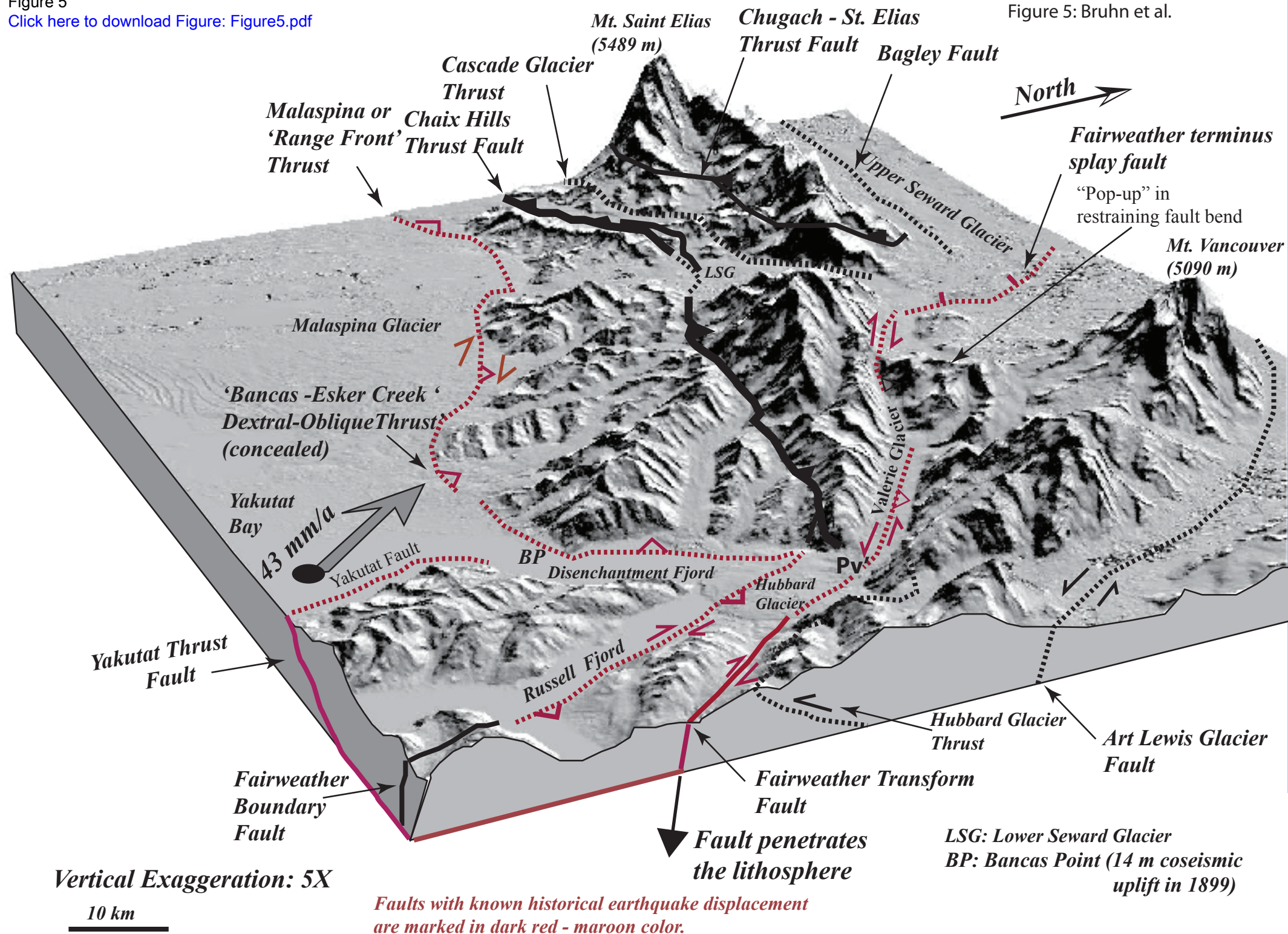
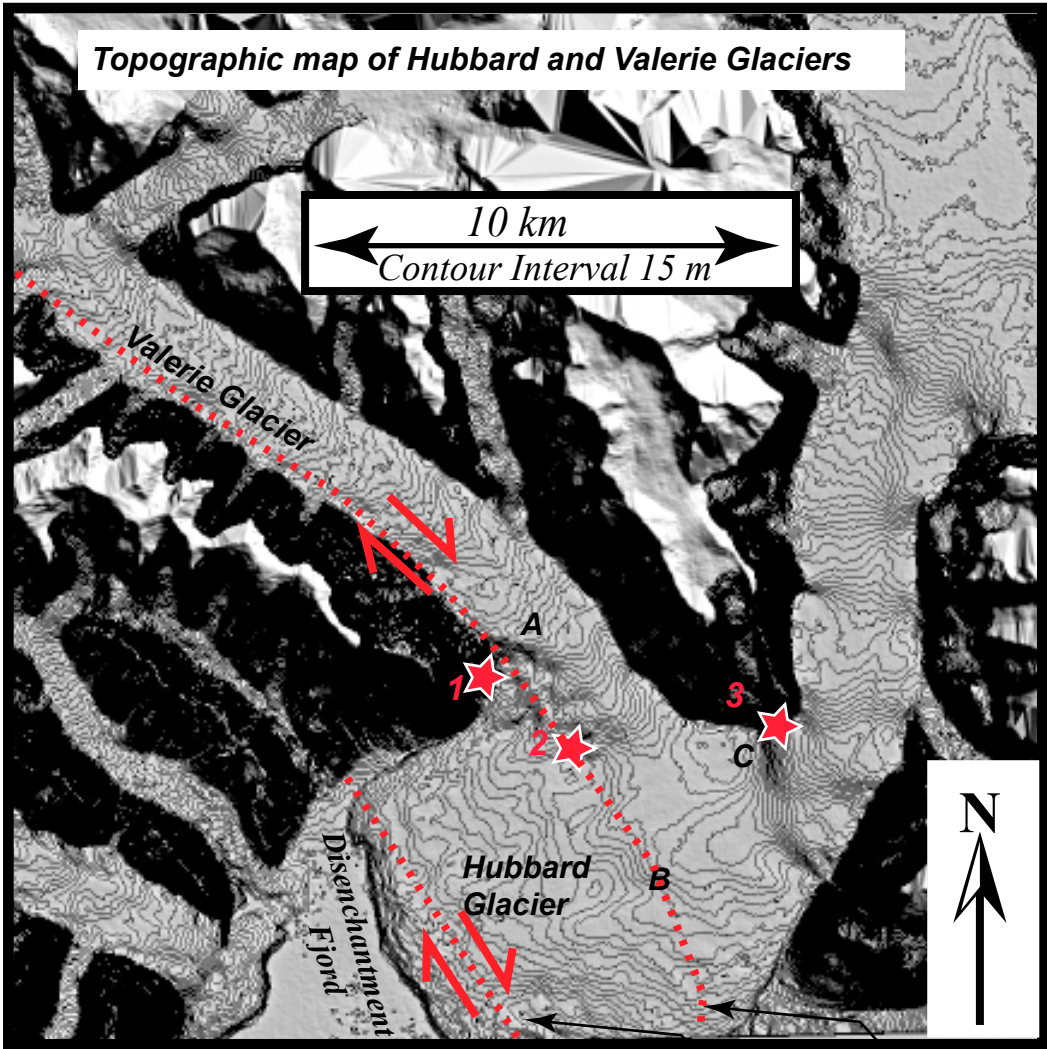


Figure 6, Bruhn et al.



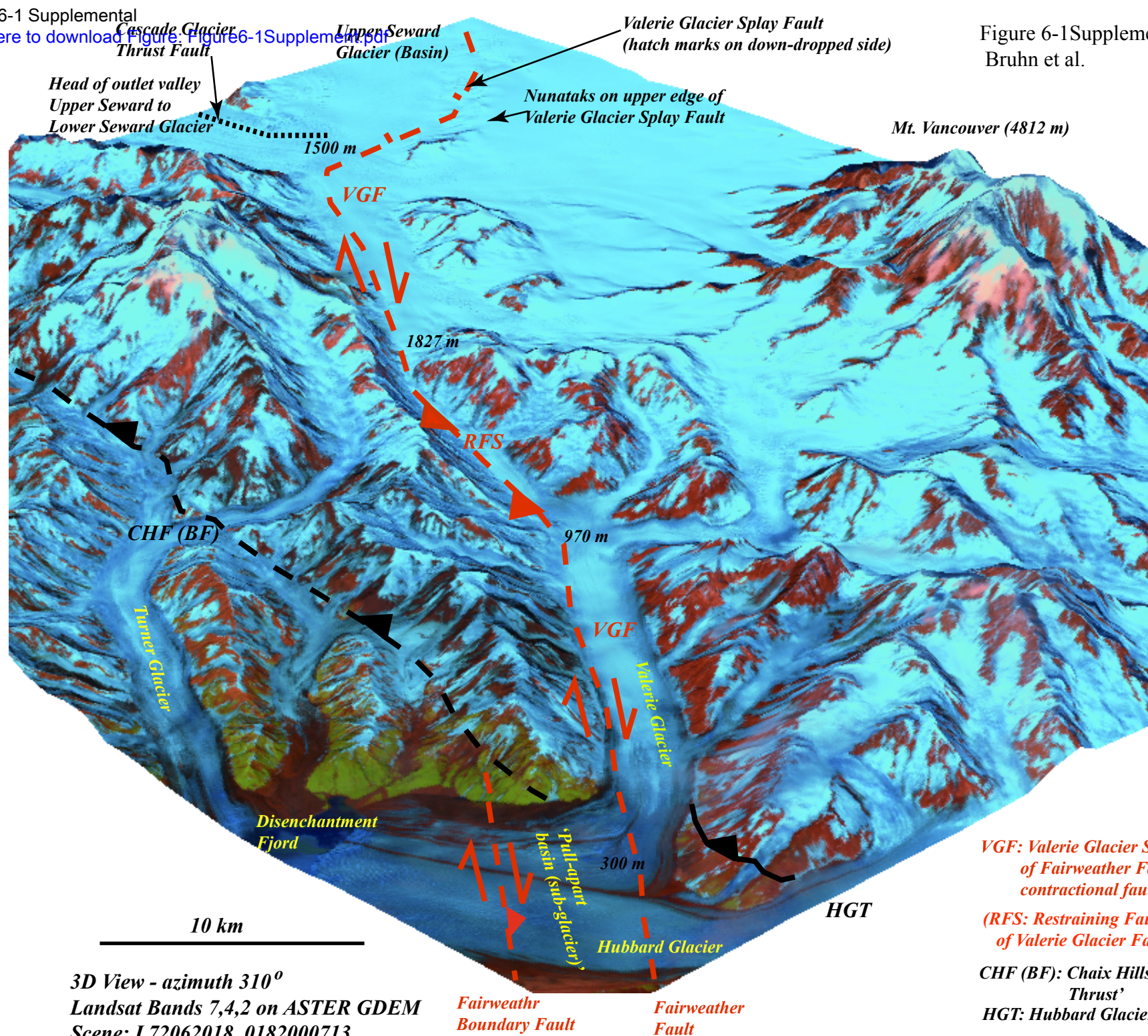
Topographic Flexures in Glacier Surfaces

- A. Ramp with cliff face on south side Valerie Glacier Fault**
- B. Projected location of Fairweather Fault**
- C. Steep flexure over lower Hubbard Glacier Thrust**

★ Marker Points for measuring
apparent dextral displacement

Fairweather
Boundary
fault

Fairweather
Fault



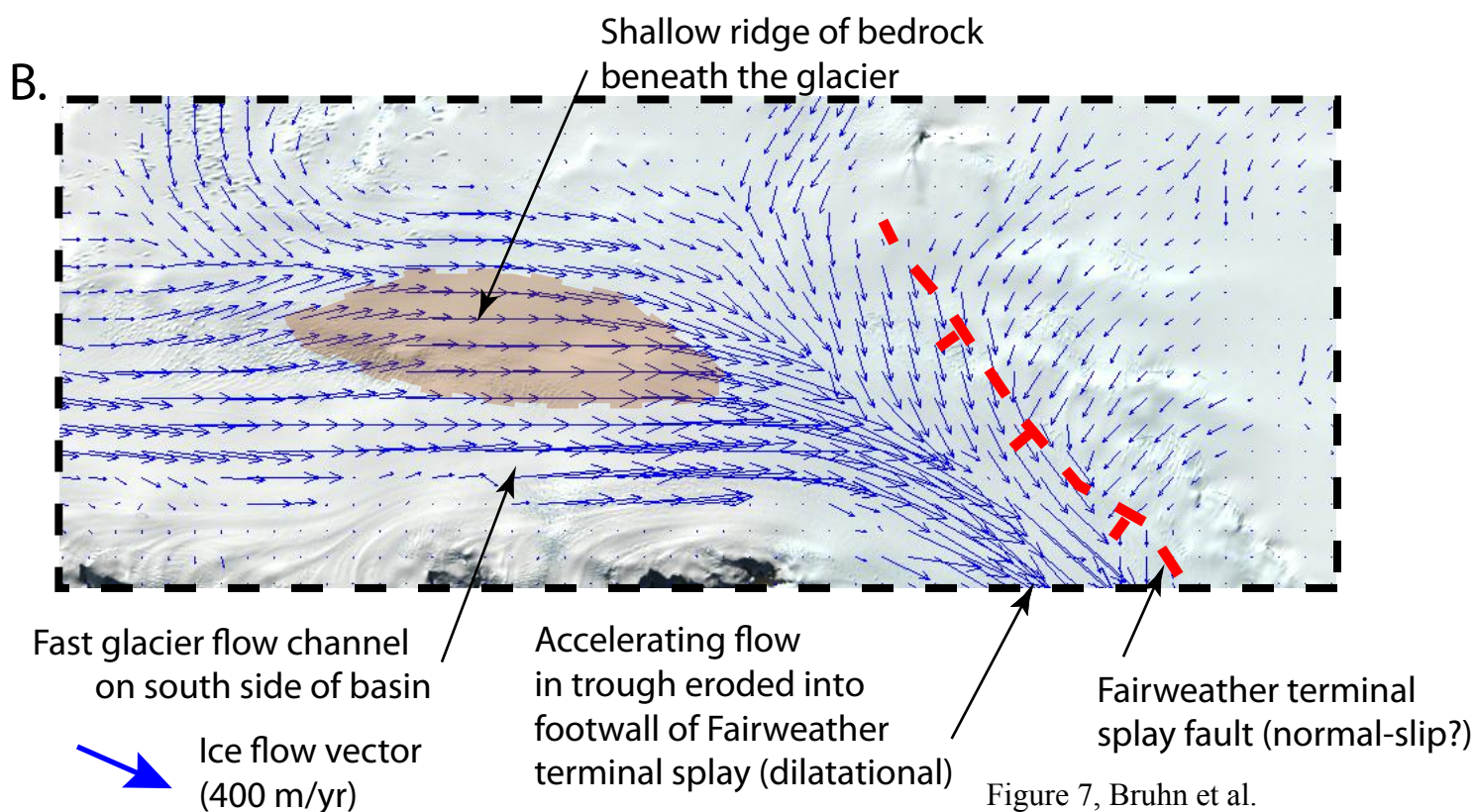
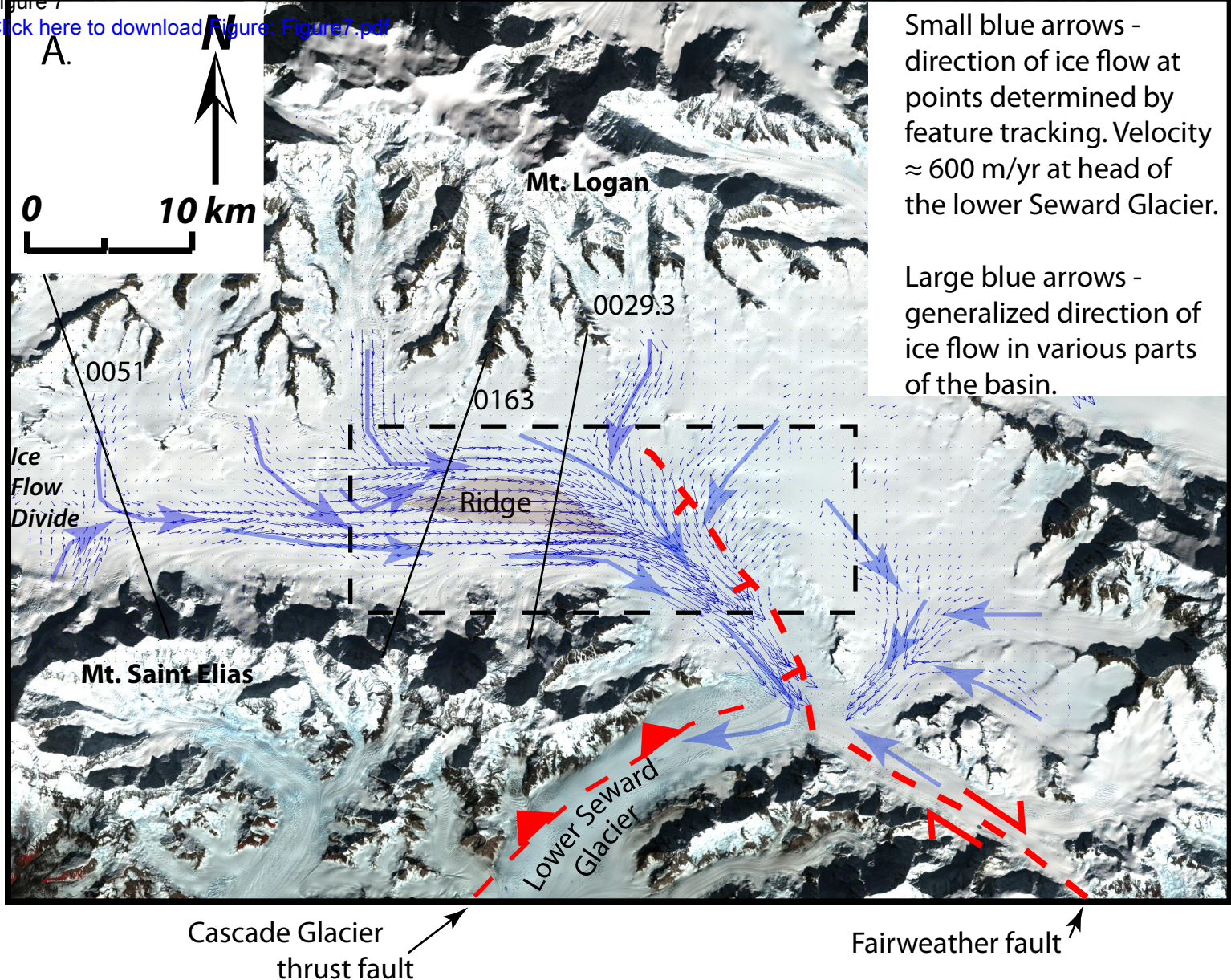
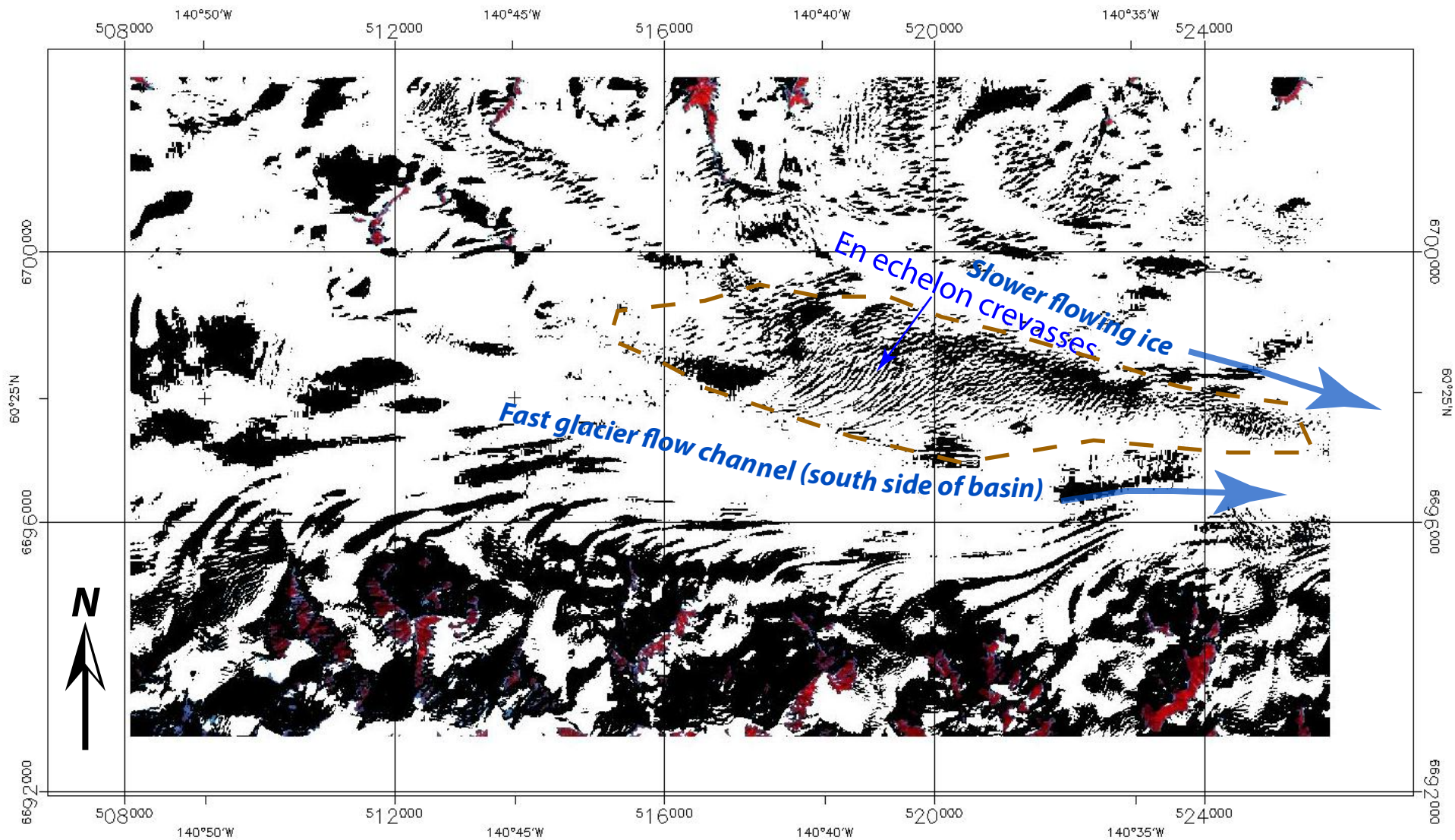


Figure 7, Bruhn et al.

Figure 7-1 Supplemental
Click here to download Figure: Figure7-1Supplement.pdf

Figure 7-1Supplement, Bruhn et al.



Legend

- Bedrock outcrops - dark red patches
- Black lines - shaded portions of crevasses
- Black elliptical to polygonal areas - shaded sides of mountains and snow covered moraine bands.
- White areas - snow covered ice
- Outline of snow and ice covered ridge of bedrock in center of basin

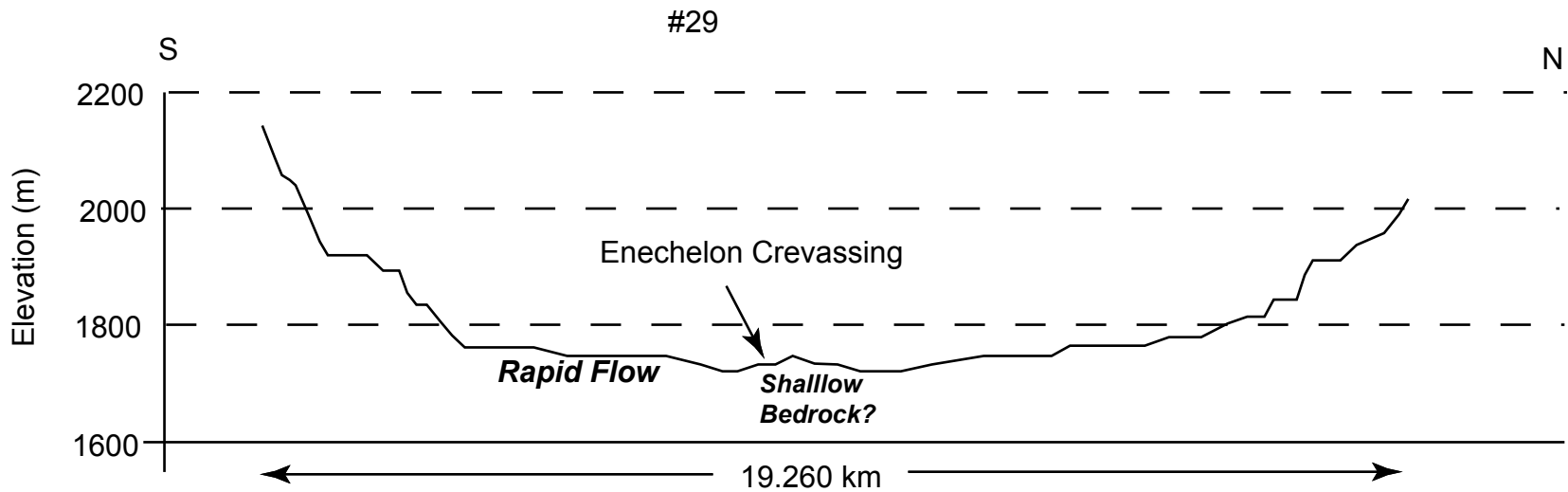
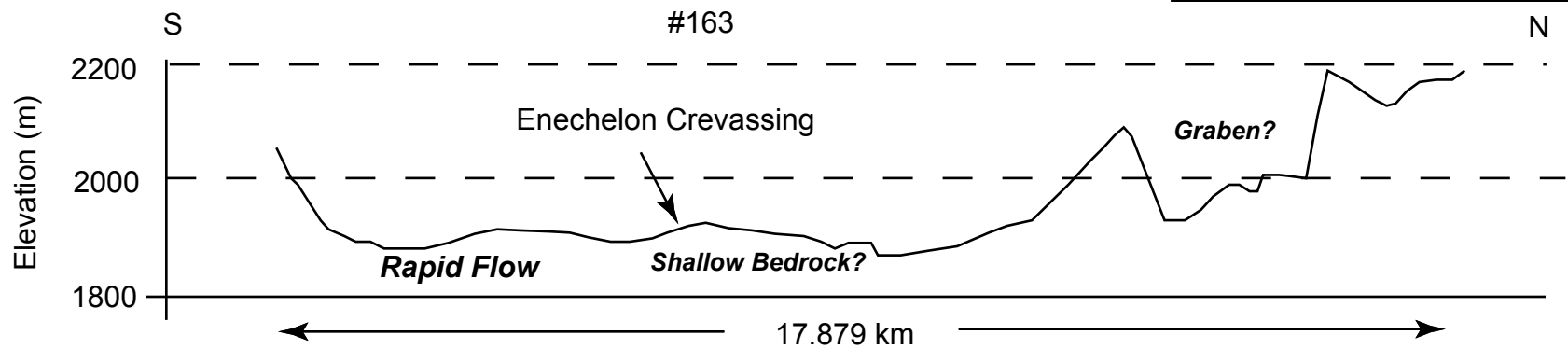
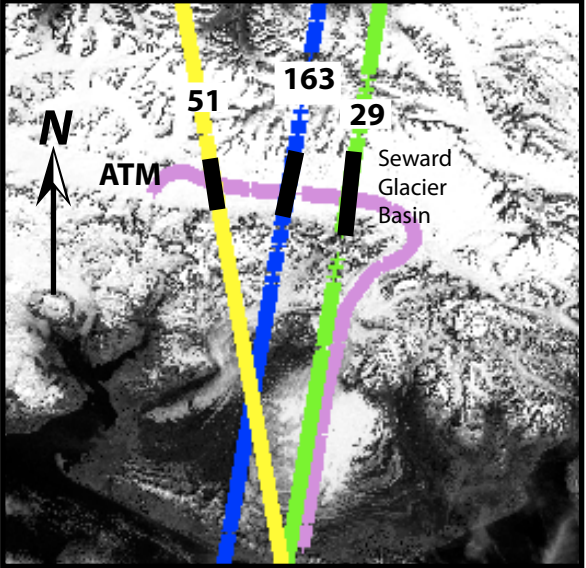
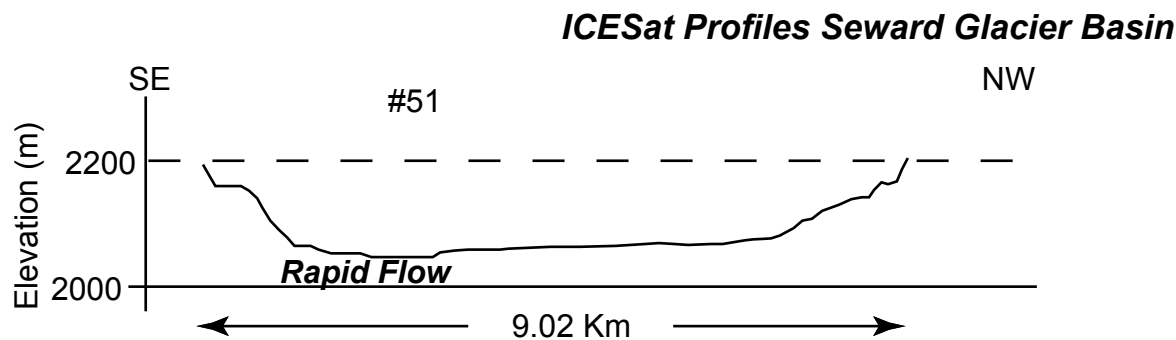
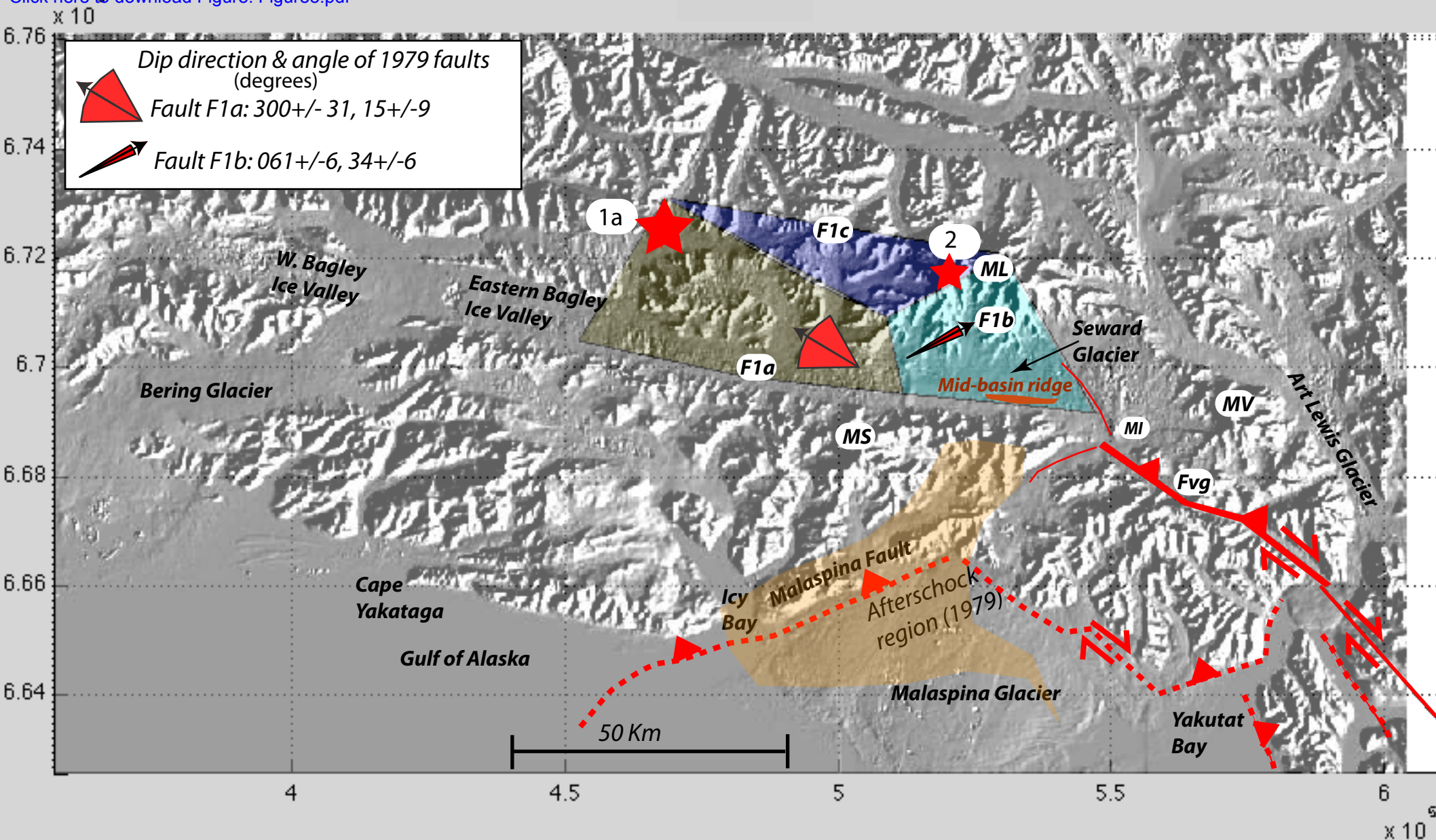


Figure 8

[Click here to download Figure: Figure8.pdf](#)

Figure 8, Bruhn et al.



Legend

Faults: F1a - Model fault for event 1a, 1979 (megathrust), F1b - Model fault for event 1b, 1979, F1c - possible fault link between F1a and F1b.

Fvg - Valerie Glacier fault segment of Fairweather Fault.

Earthquake locations: 1a - epicenter event 1a, 1979, 2 - epicenter of event 2 aftershock, 1979. Locations marked by red asterisk in each case.

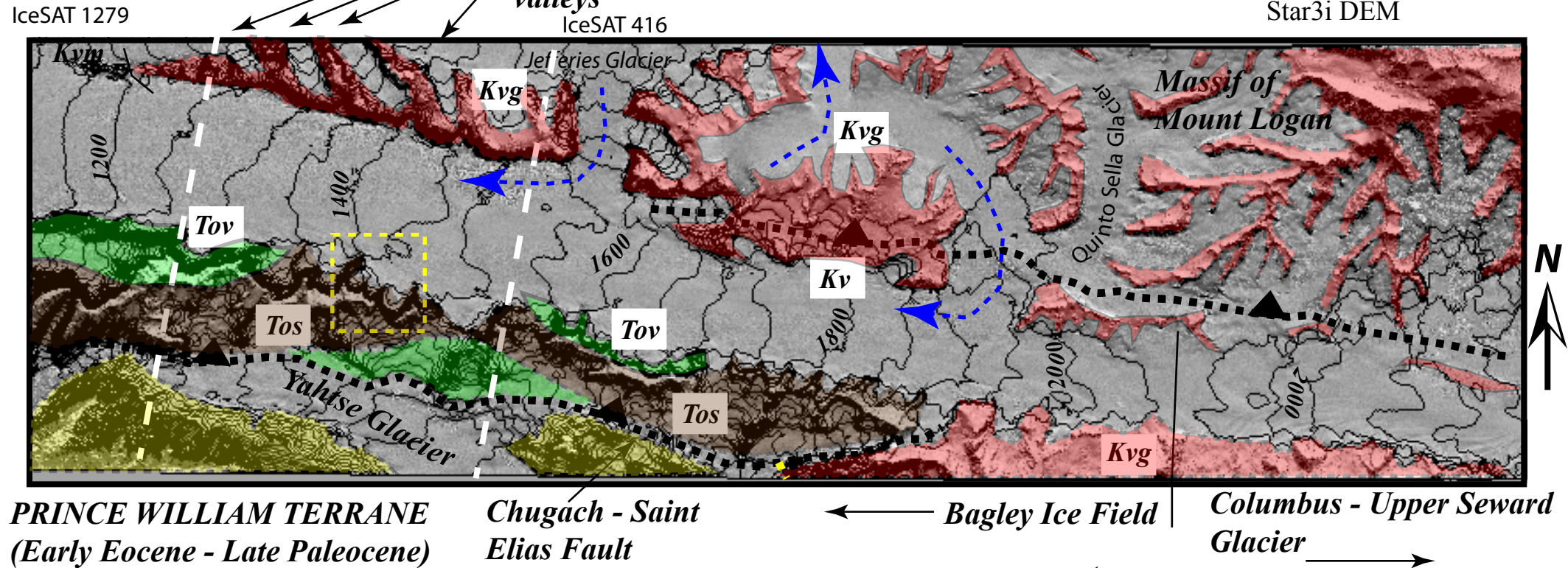
Geographic Features (short hand): MS- Mt. Saint Elias, ML-Mount Logan, MV-Mt. Vancouver, MI-Mt. Irving nunatak in Seward Glacier Basin

Coordinates: UTM Zone 7

Figure 9
[Click here to download Figure: Figure9.pdf](#)

Figure 9, Bruhn et al.

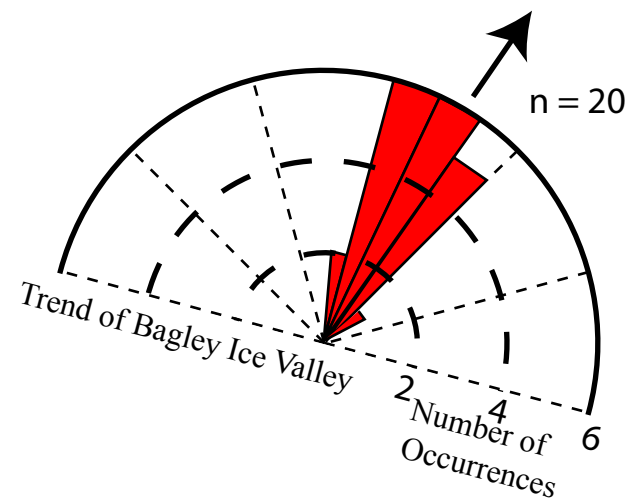
Contour Interval: 25 m
 Star3i DEM



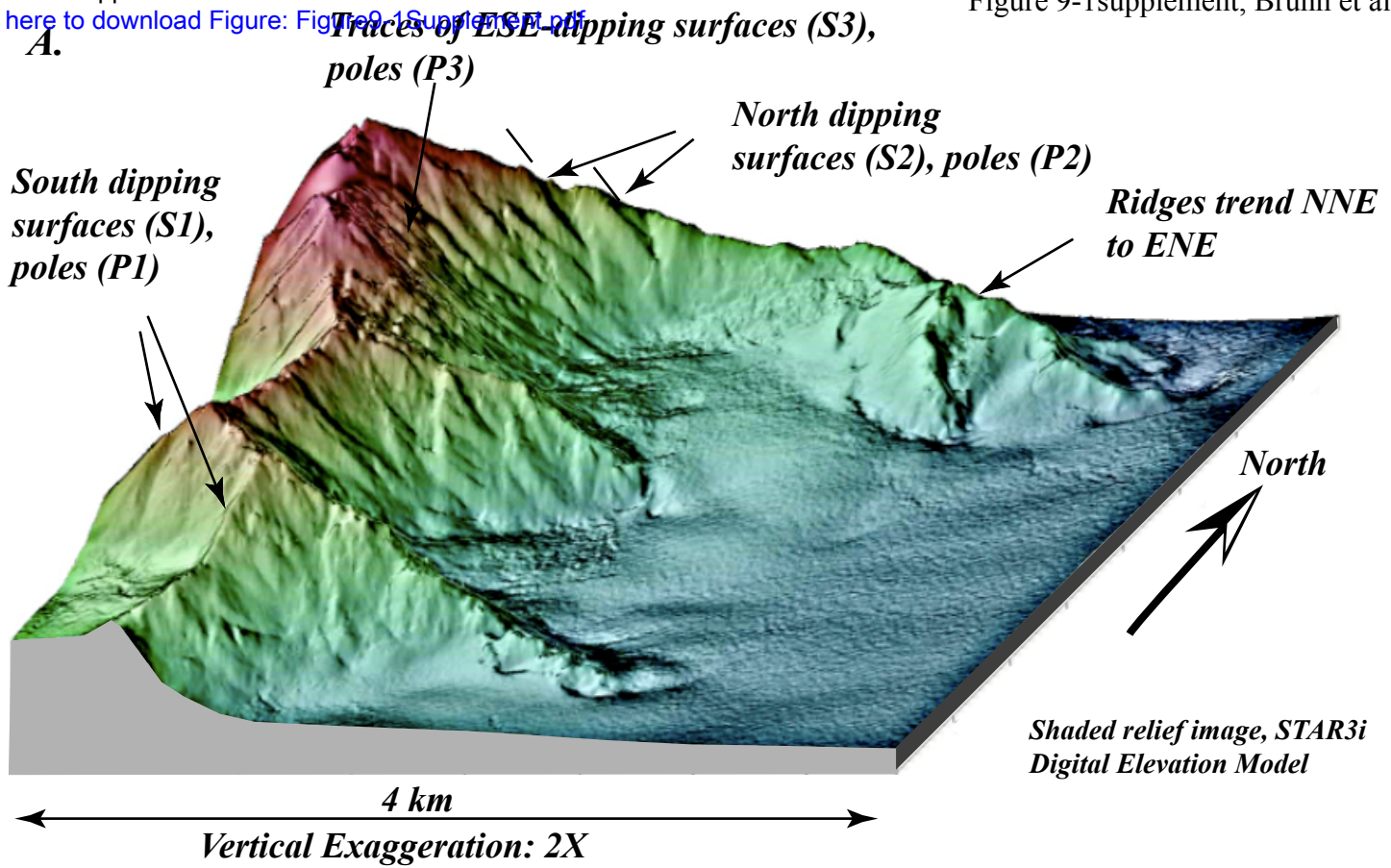
Tos - turbidites, low metamorphic grade
Tov - basalts, low metamorphic grade

CHUGACH TERRANE
 (Late Cretaceous)

Kv - Greenschist facies schist
Kvm - Amphibolite facies flysch
Kvg - Gneiss and schist



Rose diagram of cirque valley axis trends along the southern side of the Bagley Ice Valley. Average trend is 15 degrees east of normal to valley axis, and pointing up instead of down the ice flow direction of the Bagley Glacier.



B.

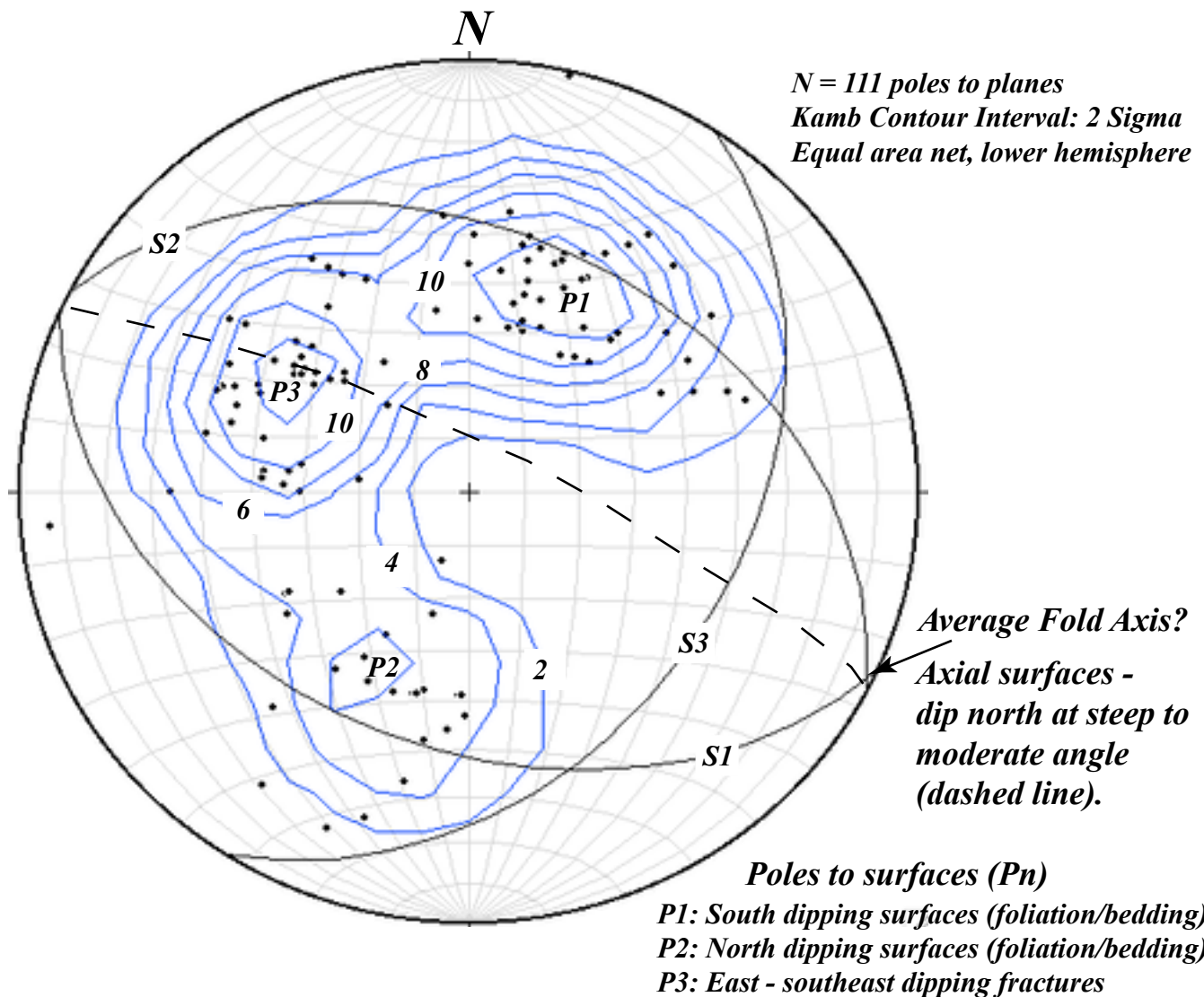
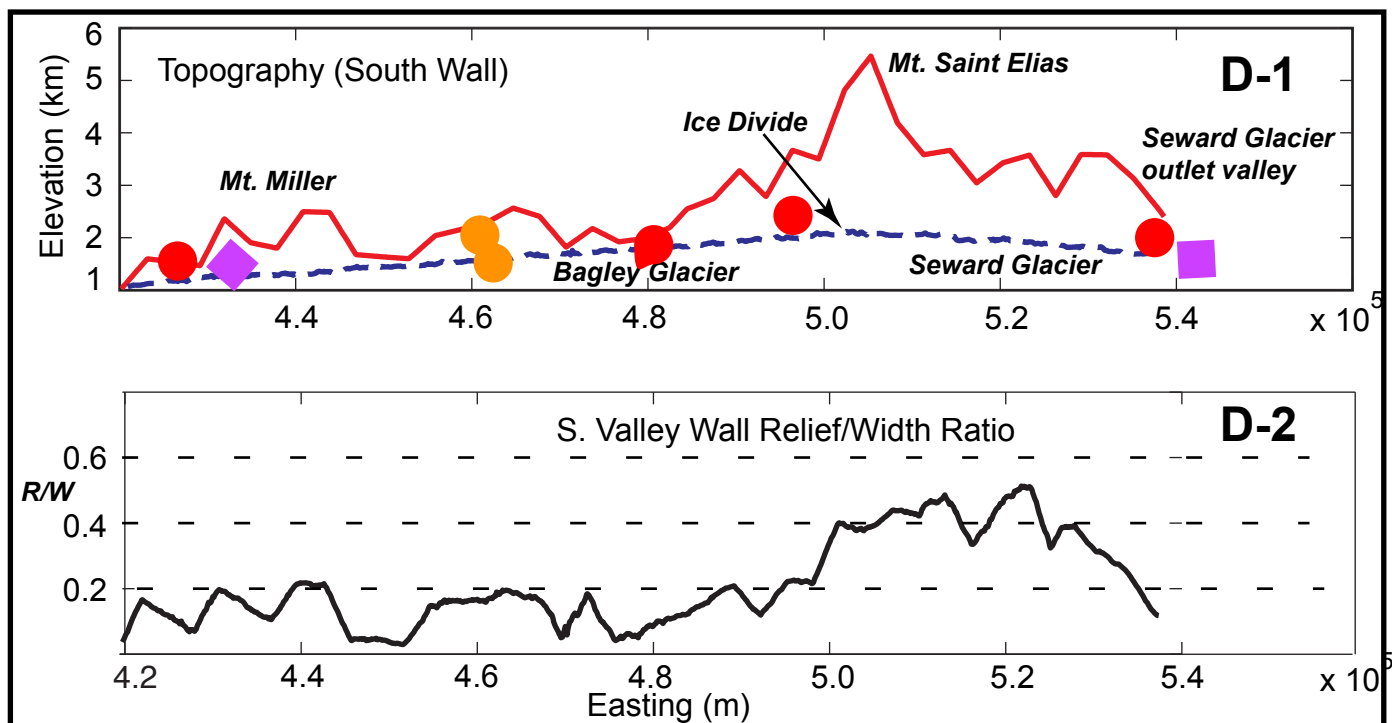
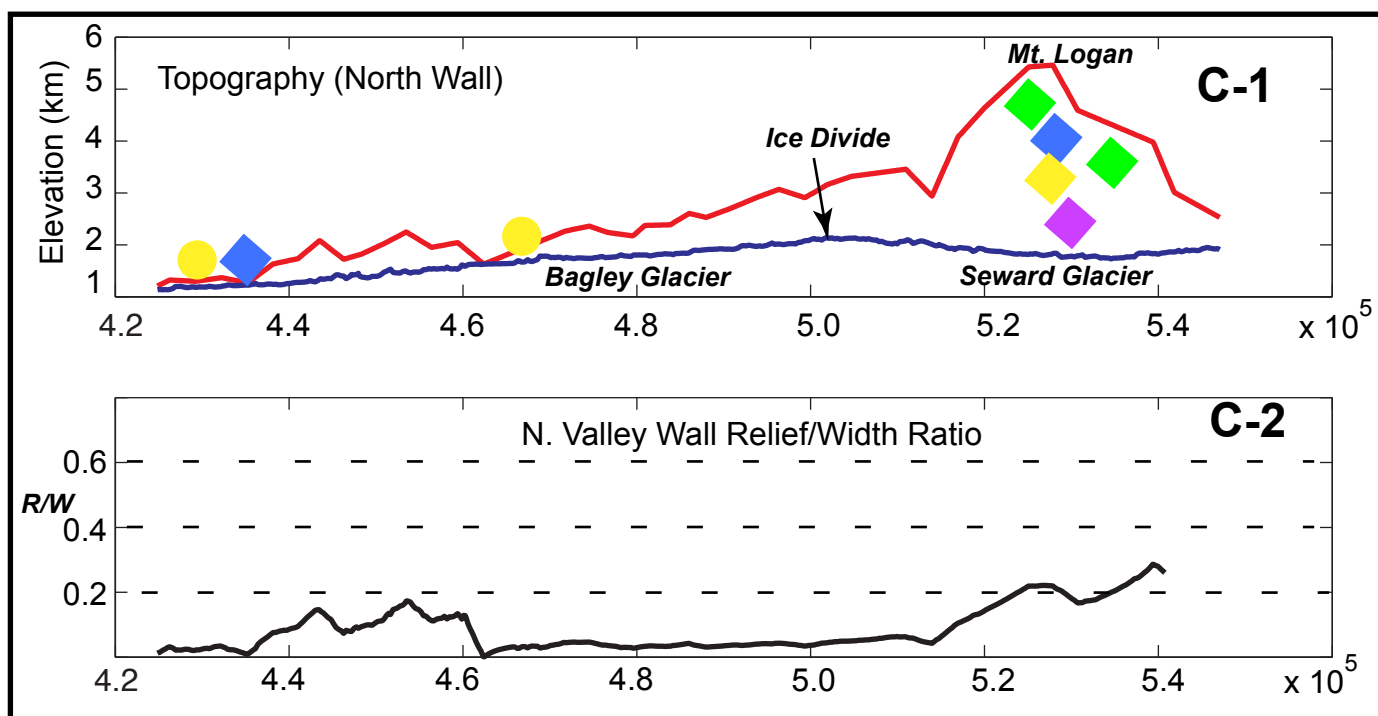
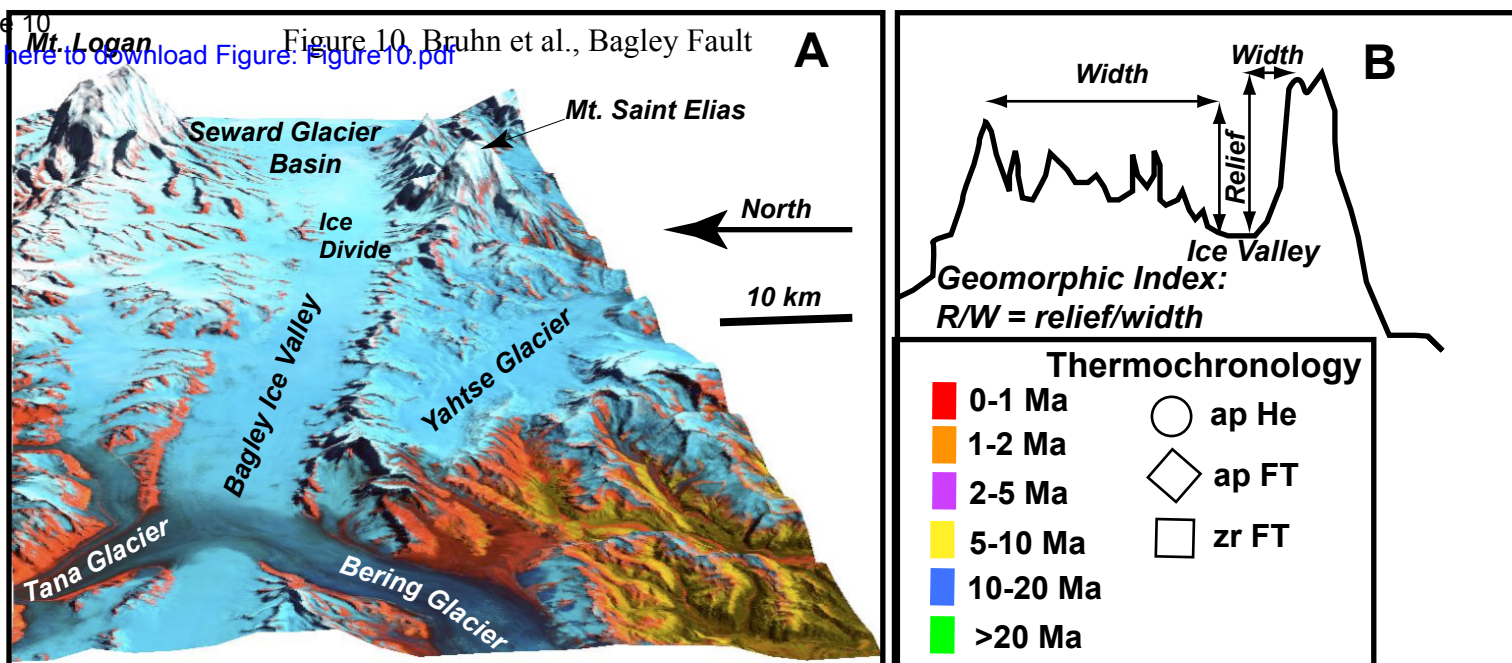


Figure 10. Bruhn et al., Bagley Fault



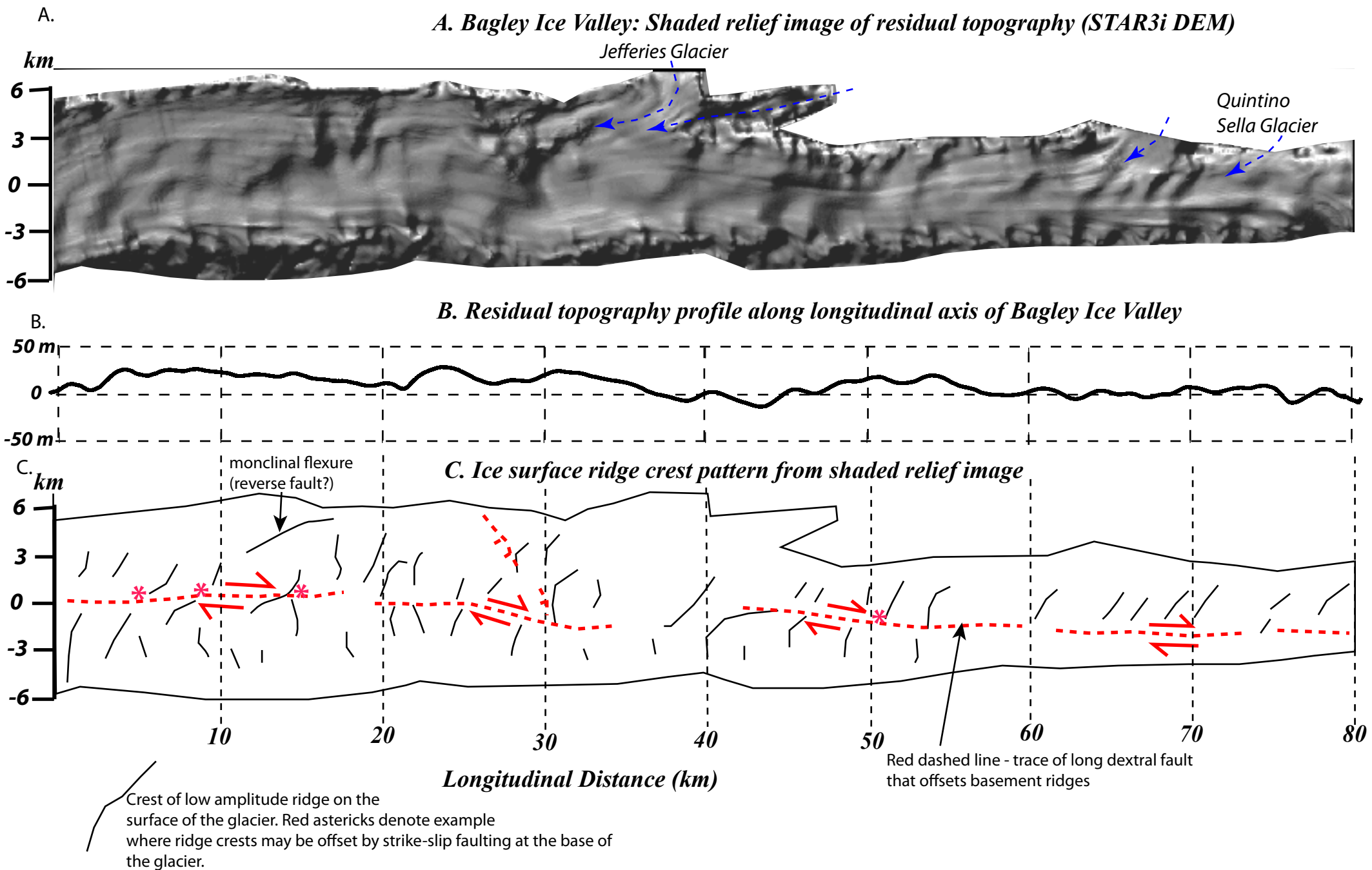


Figure 12, Bruhn and others

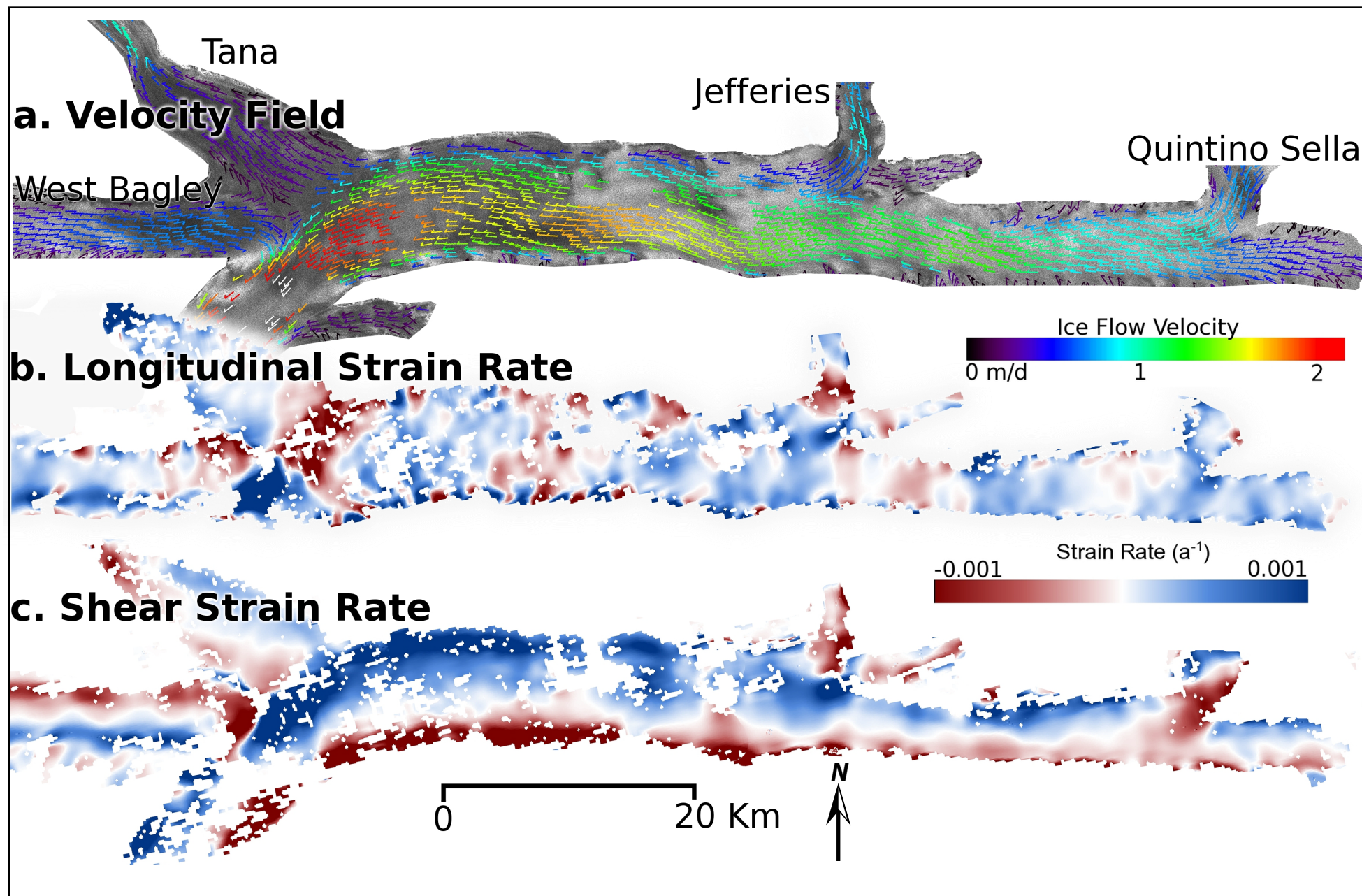
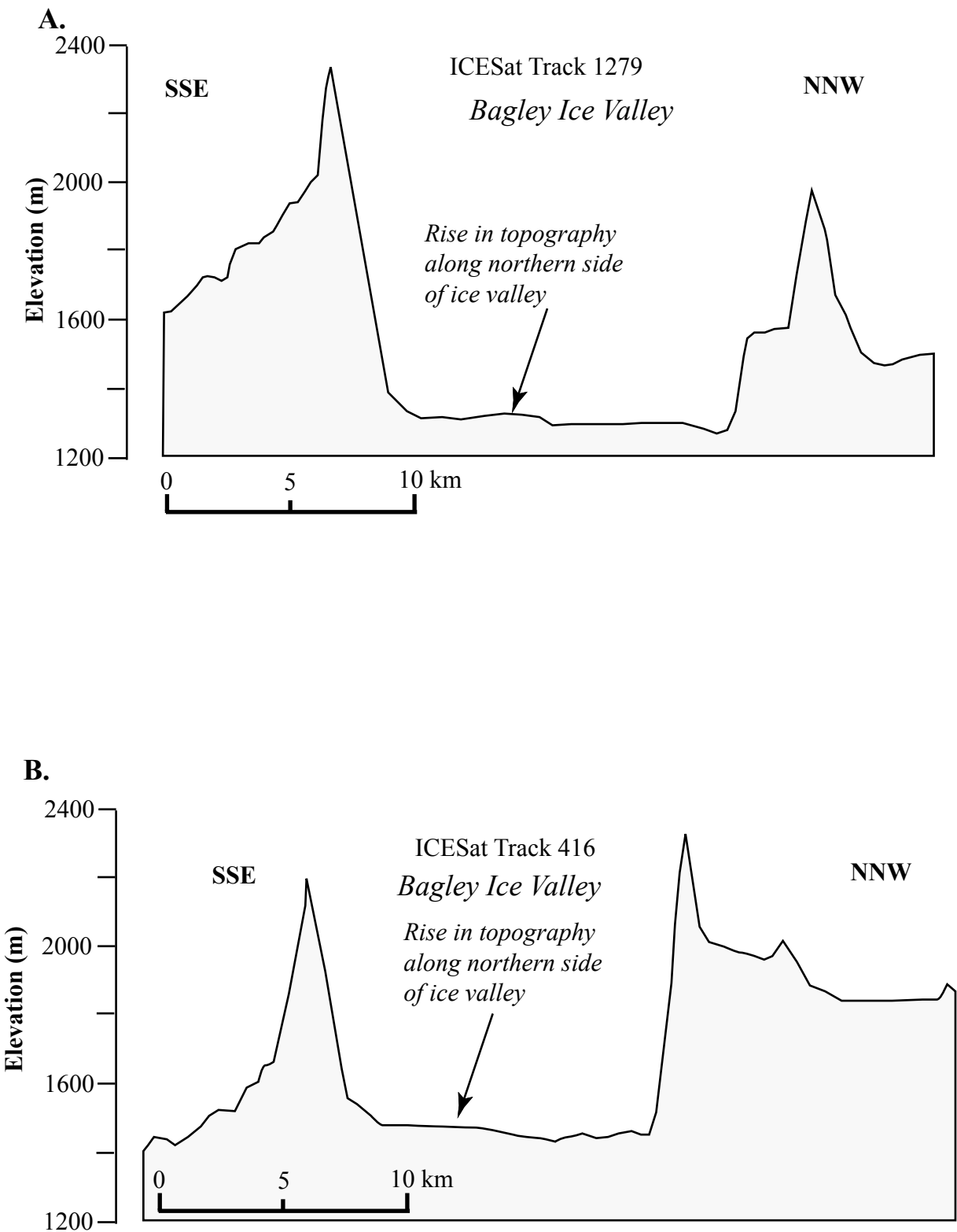
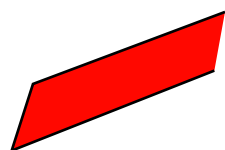
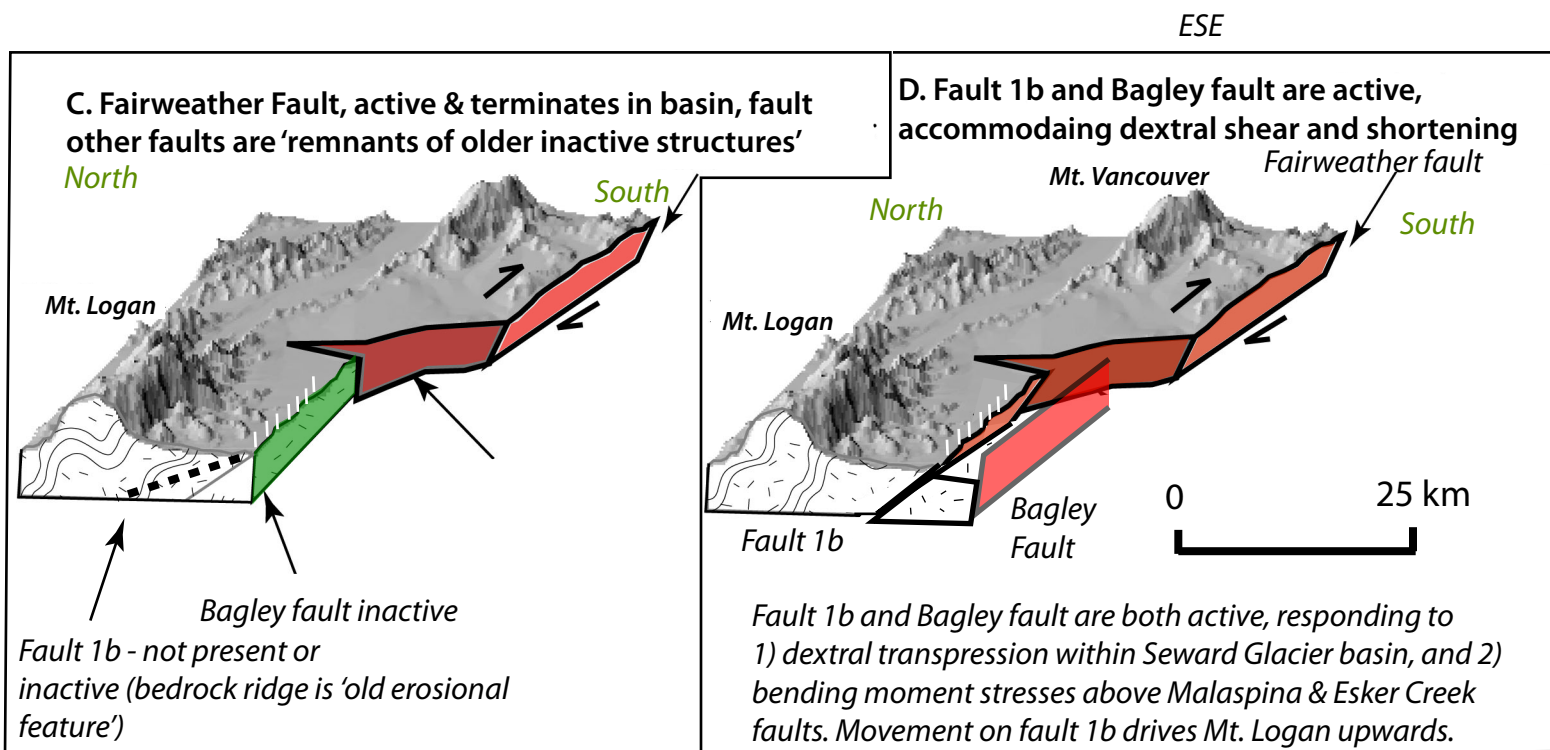
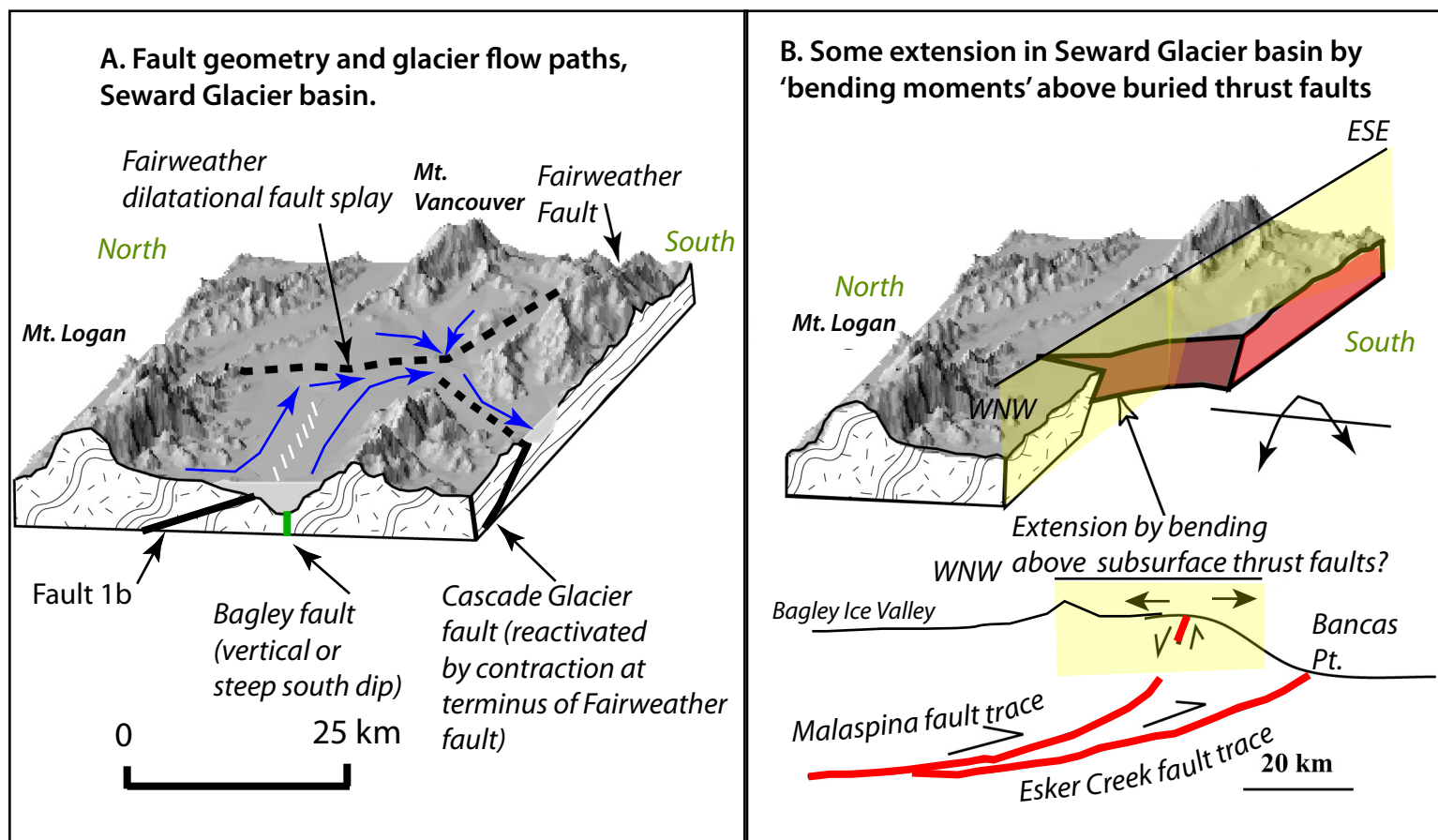


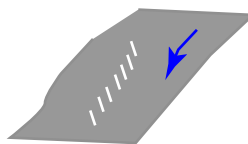
Figure 13, Bruhn et al.



Alternative tectonic scenarios for deformation in the basin of the Upper Seward Glacier (modified from models of Ford et al. (2003)).



Red-shaded fault surfaces are 'active' during the Quaternary.



White lines - en echelon crevasses along buried bedrock ridge. Blue line - ice flow path in the glacier basin

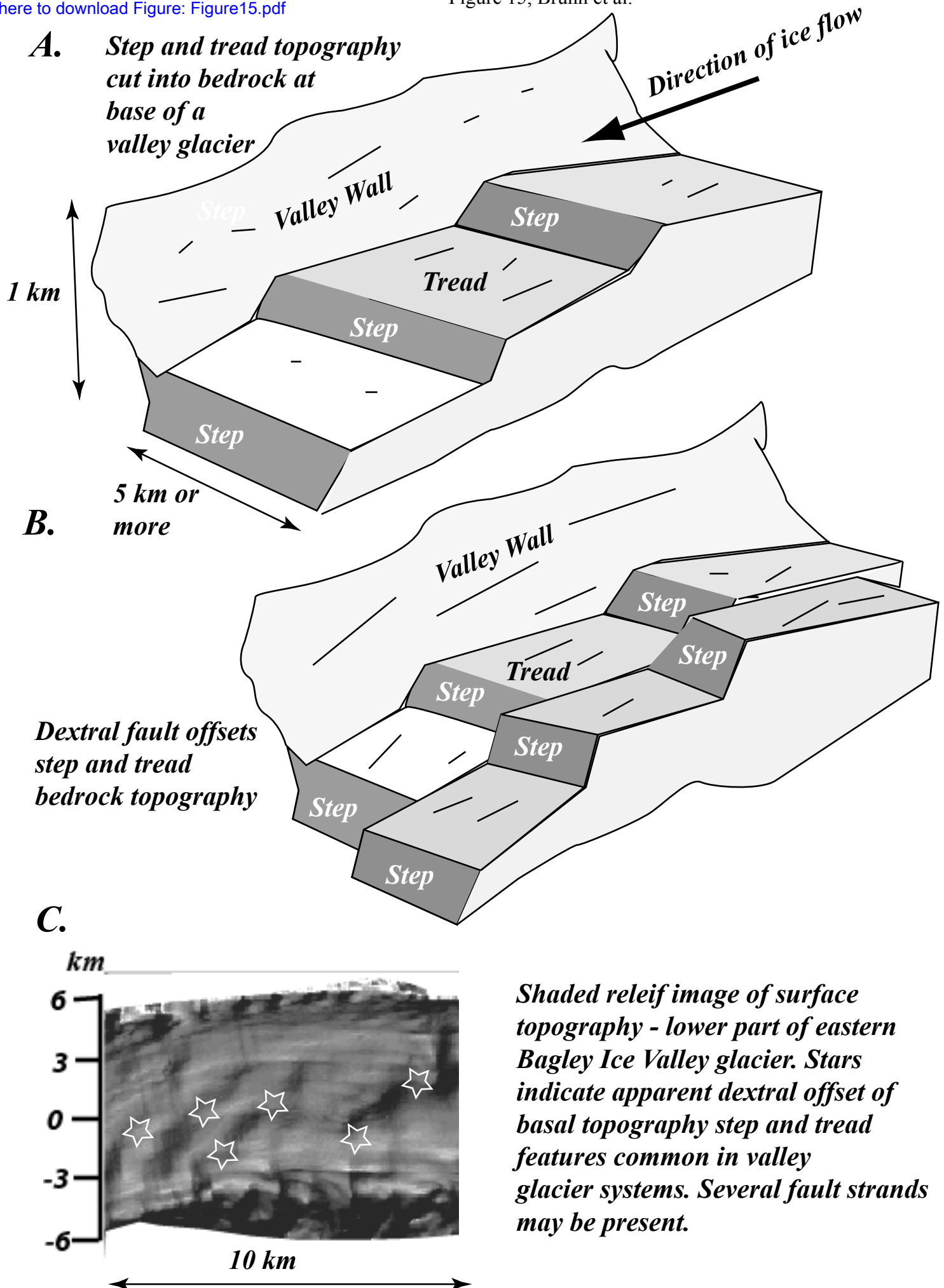


Figure 16
[Click here to download Figure: Figure16.pdf](#)

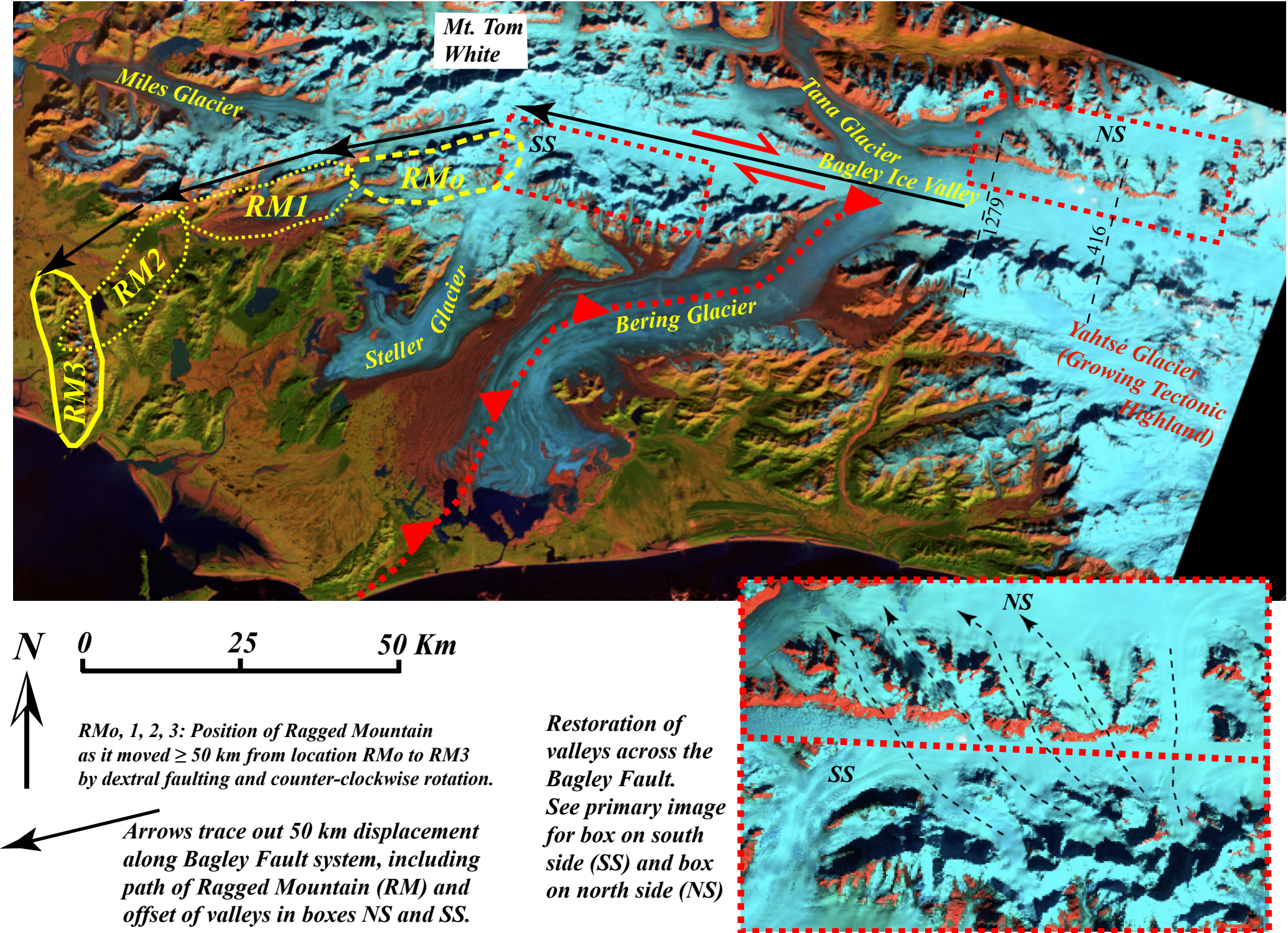
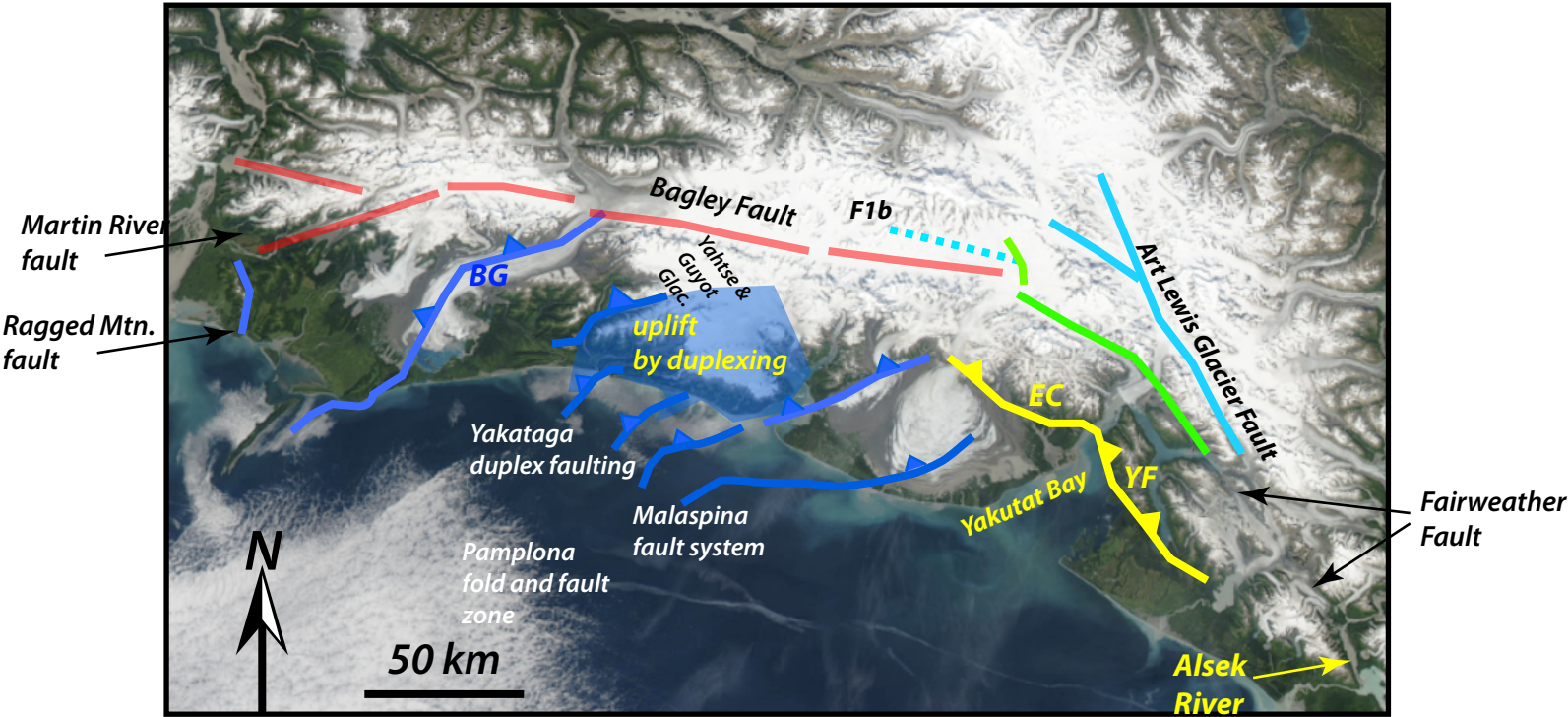


Figure 17
A MODIS satellite image of Saint Elias orogen with Bagley and other major faults

Figure 17: Bruhn et al.



B. 3D Model of major faults that link structurally to the Bagley fault

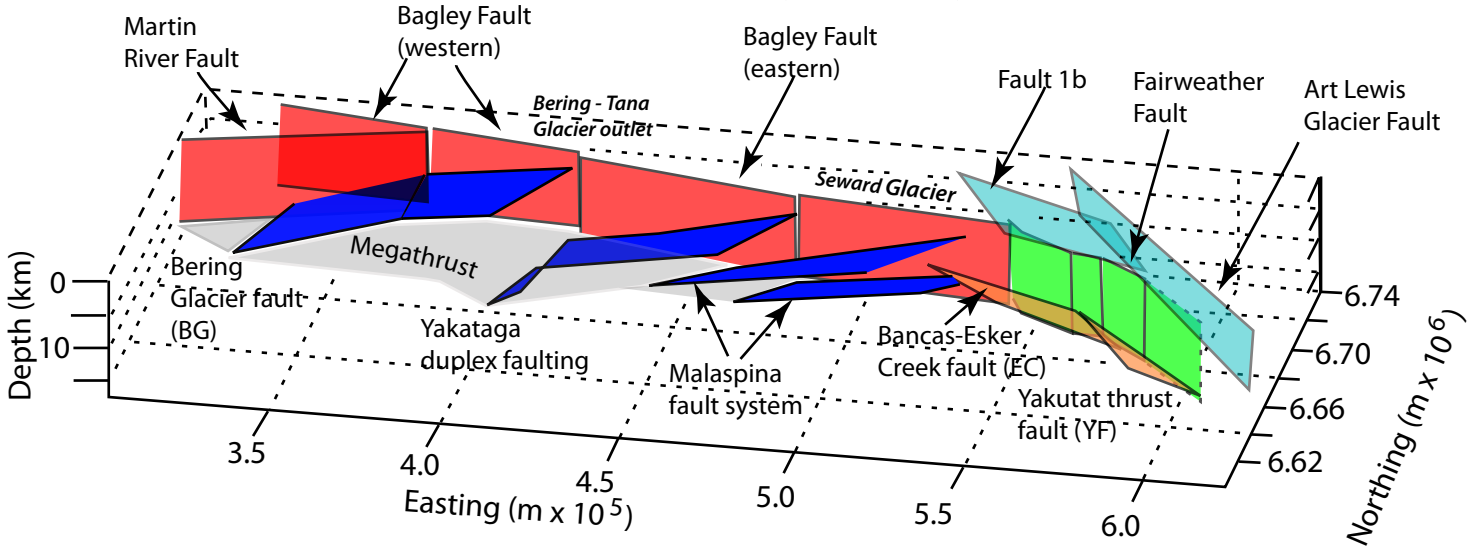


Table 1A: Faults with known Quaternary or historical displacement

Fault	Evidence for Displacement	Reference
1: Fairweather transform fault	M 7.9 earthquake, 1958	Doser (2010)
2: Fairweather Boundary fault	M 8.1 on Sept. 10, 1899 (coast uplift)	Plafker and Thatcher (2008)
3a: Yakutat thrust fault	M 8.1 on Sept. 10, 1899 (coast uplift)	Plafker and Thatcher (2008)
3b: Olomoi thrust fault	M 8.1 on Sept. 10, 1899 (coastal deformation)	Plafker and Thatcher (2008)
4: Esker & Bancas thrust fault(s)	M 8.1 on Sept. 10, 1899 (coastal uplift), dextral offset sub-glacier drainage valley	Plafker and Thatcher (2008), Cotton (2011)
5: Malaspina foreland fault	Geodetic modeling, uplift of a beach berm circa 1899 (tentative correlation).	Elliott (2011), R.L. Bruhn and I. Shennan, unpublished field notes.
6: Malaspina fault	Geodetic measurements and aftershocks to M_w 7.4 Saint Elias earthquake	Savage and Lisowski (1986), Estabrook et al. (2011), Elliott (2011)
7: Pamplona Zone thrust faults	Earthquakes up to M 6.1	
8: Cape Suckling - Bering Glacier fault	Coastal uplift M 9.2 earthquake, 1964	Plafker (1969), Chapman et al. (this volume)
9: Kayak Island	(Structural link to Bering Glacier fault)	Chapman et al. (this volume)
10: Ragged Mountain	Normal (a) and thrust faulting (b)	(a) Tysdal et al. (1976) (b) Bruhn et al. (2006)

Table 1B: Faults that may have Quaternary displacement (purple color)

Fault	Evidence for Displacement	Reference
1: Art Lewis Glacier fault	Link to Fairweather fault	G. Plafker, personal communication (2009)
2: Chaix Hills fault (western part)	May link to Fairweather Boundary fault	Geological mapping (Richter et al., 2005)
3. Cascade Glacier fault	Located in contractional lobe of the terminus of Fairweather fault.	Plafker and Thatcher (2008)
4: Sullivan fault (thrust?)	Marked by uphill facing scarp on mountainside of Sullivan anticline.	Bruhn et al. (this volume article B)
5: Miller Creek thrust fault	Mountain front and stream channel geomorphology	Chapman et al. (this volume)
6: Leeper fault (thrust)	Geodetic measurements.	Elliott (2011)
7: Bagley fault	South flank geomorphology, thermochronology	This study, Berger and Spotilla (2008); Enkelmann et al. (2009)